Bulletin
of
The Geological Society of America

VOLUME 65 April 1954 NUMBER 4

CONTENTS

Pages

Bear River and Aspen formations in Willow Creek, Teton County, Wyoming. By A. La Rocque and C. D. Edwards 315-326

Foraminiferal populations in the Grayson marl. By Claude C. Albritton, Jr., William W. Schell, Charles S. Hill, and John R. Puryear 327-336

Low-velocity layers in the Earth's mantle. By B. Gutenberg 337-348

Late Wisconsin marine drift and associated sediments of the Lower Fraser Valley, British Columbia, Canada. By J. E. Armstrong and W. L. Brown 349-364

Short Note

Lemhi arch, a mid-Paleozoic positive element in south-central Idaho. By L. L. Sloss 365-368

Subscription $15.00 per year

Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publications should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

Please give notice of change of address 4 weeks in advance. Claims for non-receipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorised on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Orogenesis and Deep Crustal Structure: Additional Evidence from Seismology. By H. Benioff

Postglacial Marine Submergence in Central Arctic Canada. By J. Brian Bird

Leaching of Wisconsin Glacial Gravels in Eastern North America. By Paul MacClintock

Petrogenesis of a Gabbro-Granophyre Complex in Northern Wisconsin. By M. W. Leighton

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 315-326, 2 FIGS. APRIL 1954

BEAR RIVER AND ASPEN FORMATIONS IN WILLOW CREEK, TETON COUNTY, WYOMING

BY A. LAROCQUE AND C. D. EDWARDS

ABSTRACT

The Cretaceous Bear River and Aspen section in Willow Creek, 6 miles southeast of the junction of the Hoback and Snake rivers, Teton County, Wyoming, is described in detail, including the position and nature of its faunas. The Bear River is 539 feet thick, and the Aspen 1307 feet thick. On lithologic and paleontologic grounds the Bear River-Aspen contact is placed lower than in earlier reports. The Aspen section contains 63 feet of porcellanite, which suggests prolonged volcanic activity in the region.

Fourteen units of the Bear River are fossiliferous, but only 2 of these, in the upper 166 feet of the formation, contain invertebrates. One assemblage is similar to the typical fresh-water Bear River fauna; the other is brackish water. The Aspen has 25 fossiliferous units, of which only 9 contain invertebrates. Seven of these are fresh water, and 2 are brackish water or marine. In no case were fresh-water and marine or brackish-water elements mixed; each fauna is distinct and separated from the others by many feet of section. Conflicting age assignments for the Bear River and Aspen are discussed.

CONTENTS

TEXT

	Page
Introduction	315
Stratigraphy	317
Bear River section	317
Aspen section	317
Discussion	320
Paleontology	321
Bear River faunas	321
Aspen faunas	321
Discussion	324
Formation boundaries	324
"Mixed faunas"	324
Nature of the Aspen faunas	324
Age of the Bear River and Aspen formations	325
References cited	325

ILLUSTRATIONS

Figure	Page
1. Index map	316
2. Sketch map of Willow Creek	316

INTRODUCTION

This study of Bear River and Aspen beds in a small area of southern Teton County, Wyoming (Figs. 1, 2), was the result of an assignment at Camp Davis, geological field station of the University of Michigan, in the summer of 1946. A report was prepared in the autumn of 1946, but the results were considered of little general interest. Recent discussion of the age of the Bear River formation (Yen, 1952, p. 761–762) and the publication of Cobban and Reeside's (1952) correlation tables have prompted re-examination of the work; the writers now believe that their study may contribute something to the discussion of the age of the Bear River and Aspen formations.

The area studied is in southern Teton County, west-central Wyoming, 6 miles southeast of the junction of the Hoback and Snake rivers (Figs. 1, 2). Willow Creek is a tributary of the Hoback River and in turn has a number of smaller tributaries. The valley of Willow Creek is generally broad, but in places it narrows to a steep-walled canyon; its slopes expose a number of good sections of the Bear River, Aspen (Albian or Cenomanian), and Frontier (Cenomanian and Turonian) formations, and, in one place at least, the top of the Gannett formation (Aptian) is exposed.

Three problems were investigated: (1) delimitation of the boundary between the Bear River and Aspen, on lithologic and paleontologic grounds; (2) nature of the "mixed faunas" of the Bear River; (3) nature of the faunas of the Aspen.

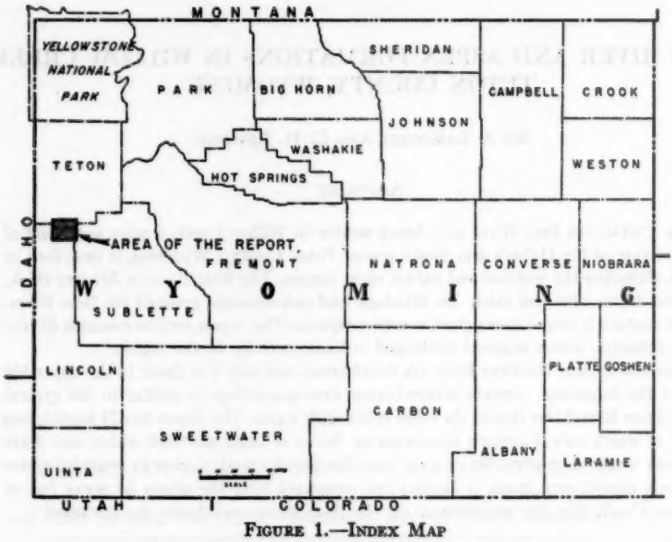

FIGURE 1.—INDEX MAP
Showing location of area of the report (Fig. 2).

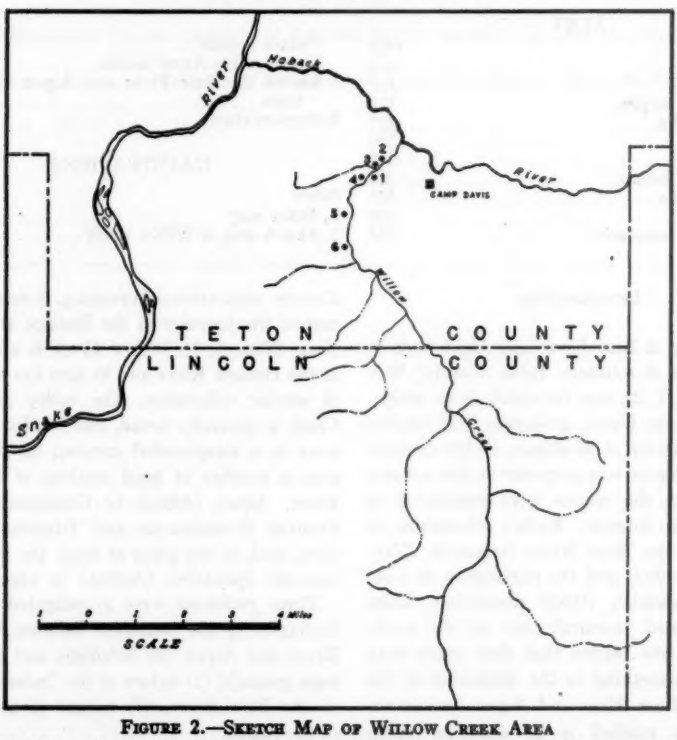

FIGURE 2.—SKETCH MAP OF WILLOW CREEK AREA
Showing localities where sections were measured. Bear River section: (1) Units 1–14, (2) Units 15–23; Aspen section: (3) Units 1–7, (4) Units 8–81, (5) Units 82–92, (6) Units 93–105.

The writers are indebted to Profs. R. L. Belknap and A. J. Eardley for suggesting the problem and to Profs. H. R. Wanless and L. B. Kellum for advice and direction in the field. Dr. J. B. Reeside, Jr., has given many valuable suggestions which are gratefully acknowledged; specific points which he has contributed are noted in the text. The fossils collected during this study have been deposited in the Museum of Paleontology of the University of Michigan.

Stratigraphy

Bear River Section

The following section of the Bear River formation was measured in Willow Creek, and fossils were collected unit by unit wherever they were found. Units 1–14 were measured on the east side of Willow Creek in the canyon wall east of the first landslide above its mouth (Fig. 2, locality 1). Here the lowest bed of the Bear River rests on purplish-red shales and limestones of the Gannett formation (Lower Cretaceous). The remainder of the section was measured on the west side of Willow Creek in the slopes about half a mile downstream from the landslide area (Fig. 2, locality 2).

Unit No.		*Thickness (Feet)*
	Aspen formation	
	Bear River formation:	
23	Shale, black, purple, splintery (top of Bear River) hard, limonite stains ...	65
22	Sandstone, dark gray, weathering light gray, fine-grained, calcareous, plant fragments, ripple marks.....	1
21	Shale, black, purple, hard, splintery, limonite stains. Gray limestone, weathering brown, found as float....	26
20	Sandstone, light gray, fine-grained, fucoidal, finely banded, limonite stains.....	1
19	Coquina, gray, weathers red, yellow, gray, fine-grained sandstone matrix, massive, blocky. Contains *Ostrea* cf. *haydeni* White and *Modiolus* cf. *pealei* (White) in great abundance...	1
18	Sandstone, gray, weathering gray to greenish-gray, medium-grained, finely banded, blocky, fucoidal.....	3
17	Shale, black, hard, blocky, limonite stains.....	66
16	Coquina, gray, black, weathering dark gray to brown, calcareous. Contains "*Unio*" cf. *velustus* Meek, Naiades (3 species), *Corbula* cf. *engelmanni* Meek, *Pyrgulifera humerosa* Meek, *Campeloma* cf. *macrospira* Meek, *Lioplacodes* sp., *Goniobasis* (2 species), *Charydrobia* sp., *Hydrobia* sp., *Valvata* sp., *Amnicola* (?) sp.....	2
15	Shale, black, splintery.....	19
14	Sandstone, tan, gray on fresh surface, massive, prominent vertical jointing, some thin-bedded calcareous sandstone near base.....	48
13	Covered interval, probably black shale.....	43
12	Sandstone, tan, gray on fresh surface, thin-bedded and cross-bedded, fucoidal shale partings, lower 6 feet is carbonaceous and contains plant fragments.....	30
11	Lignite, poorly consolidated.....	0.5
10	Sandstone, interbedded with black carbonaceous shale. Sandstone is white, friable, slightly calcareous, thin-bedded; sandstone grades into tan sandstone below.....	7
9	Sandstone, tan, gray on fresh surface, generally massive, jointing prominent, basal 6 feet interbedded with carbonaceous shale.....	27
8	Lignite; contains one fossil gastropod, too poorly preserved for identification.....	0.4
7	Sandstone, tan to brown, weathering gray to brown, massive, vertical jointing, plant fragments.....	5
6	Sandstone and shale, interbedded. Sandstone is black, carbonaceous, weathering tan; shale is black, carbonaceous, fucoidal.....	12
5	Sandstone, tan, carbonaceous, plant fragments.....	5
4	Shale, black, splintery, hard.....	160
3	Sandstone, white, gray, weathering buff, very fine-grained, grades to greenish-gray fine-grained sandstone; limonite stains.....	5
2	Siltstone, gray green, weathering gray to buff, some glauconite, hard, some very thin shale partings, grades locally to a very fine-grained ripple-marked sandstone.....	12
1	Mudstone, green, glauconitic, grades into a green siltstone, poor plant fragments.....	2
	Total thickness of Bear River...	540.9
	Gannett formation:	
	Siltstone (top of Gannett formation), red, purple, maroon, fractured, blocky.....	5 (partial)

Aspen Section

Units 1–7 were measured in the first ridge north of the first unnamed tributary of Willow

Creek (Fig. 2, locality 3); units 8–81 in the second ridge south of this tributary (Fig. 2, locality 4); units 82–92 in the fourth ridge of the same creek (Fig. 2, locality 5); and units 93–105 in the ridge on the west side of Willow Creek about 2 miles above the mouth of the first unnamed tributary of Willow Creek (Fig. 2, locality 6).

Unit No.		Thickness (Feet)
	Frontier formation	
	Aspen formation:	
105	Sandstone, tan, hard, coarse-grained, generally massive, some cross-bedding, contains fossil wood and plant fragments, cliff-former (top of Aspen formation)	80
104	Covered interval, some green glauconitic siltstone exposed near base, evidence of a blue-gray siltstone near middle of interval, tan sandstone float at top	123
103	Sandstone, blue gray, fine-grained, blocky	3
102	Covered interval, some green glauconitic siltstone exposed in top half	28
101	Sandstone, "salt-and-pepper", coarse-grained, hard, calcareous, massive to thin-bedded and cross-bedded, ledge-former	17
100	Siltstone, green, glauconitic, grading to blue gray	72
99	Sandstone, gray green and blue gray, weathering green, gray, and brown, hard	6
98	Siltstone, green, glauconitic	23
97	Sandstone, blue gray, weathering gray with red spots of included porcellanite, calcareous	0.5
96	Conglomerate, blue gray, pebbles of porcellanite in gray sandstone matrix	1
95	Covered interval	5
94	Porcellanite, red, green, pink, blue, hard, brittle, well-bedded; spotted and banded porcellanite common	5
93	Siltstone, green, glauconitic	43
92	Sandstone, blue gray, weathering gray, calcareous, fossil wood	4
91	Siltstone, green, glauconitic, some blue gray	43
90	Sandstone, gray, cross-bedded, weathered surface at top of interval similar to weathered porcellanite	2
89	Siltstone, blue gray, green, glauconitic, siliceous	10
88	Sandstone, green, medium-grained, glauconitic, grades locally to sandy siltstone	3
87	Siltstone, blue gray, green, glauconitic	12
86	Sandstone, gray, banded (biotite conspicuous), cross-bedded, hard	10
85	Siltstone, blue gray, green, siliceous, hard, grading locally to a fine-grained, blue-gray sandstone	9
84	Sandstone, blue gray, weathers gray and green, calcareous, hard, massive	3
83	Covered interval	5
82	Siltstone, green, glauconitic, blue, blue gray, siliceous, hard	14
81	Porcellanite, blue, speckled with white	5
80	Siltstone, green, glauconitic, siliceous, very hard, splintery fracture, some interbedded sandstone that resembles reworked porcellanite	10
79	Sandstone, light gray, medium-grained, contains much reworked porcellanite	3
78	Porcellanite, blue, black, purple, green, bedded, spotted with white or banded, very hard, generally fractured, fossil ferns, fossil wood	32
77	Sandstone, tan, medium-grained, jointing conspicuous, plant fragments	13
76	Siltstone, green, glauconitic grading to a blue-gray, cross-bedded, fine-grained, calcareous sandstone with black carbonaceous shale partings. The sandstone contains: *Myalina?*, *Modiolus* sp., *Macoma?*, *Arca* sp., *Pecten?* (fragment), undetermined gastropod, crustacean claw?, fucoids	10
75	Sandstone, gray, medium-grained, contains reworked porcellanite	3
74	Porcellanite, blue gray, weathers blue, green, gray, conchoidal fracture, massive, plant fragments abundant	10
73	Sandstone, green, weathering gray, glauconitic, very fine-grained	1.5
72	Porcellanite, blue green, speckled with white	2
71	Shale, black, splintery, fossiliferous, contains fossil wood, *Lymnaea* sp., *Campeloma* sp., *Lioplacodes* sp., *Goniobasis* sp., other undetermined gastropods	6
70	Sandstone, gray, blue gray, fine to medium-grained, conglomeratic at top (pebbles of porcellanite), cross-bedded, thin-bedded, plant fragments	11
69	Siltstone and shale, interbedded. Siltstone is green, glauconitic, blocky; shale is blue-gray, black, splintery	14
68	Limestone, gray, fossil plant roots	2

Unit No.		Thickness (Feet)
67	Shale, blue gray, splintery, calcareous, fractured, plant fragments	2.5
66	Limestone, blue gray, weathering gray	5
65	Siltstone, blue gray, weathering green, fractured	1.5
64	Shale, black, plant fragments, contains *Corbula?* sp., *C.* cf. *engelmanni* Meek, *Glycymeris?*, 3 undetermined pelecypods, *Modiolus* sp., *Pyrgulifera? Cerithium?*, *Rhytophorus?*, *Bithynella?*, ostracode	5
63	Sandstone, gray, weathering gray to tan, plant fragments	2.5
62	Covered interval	8
61	Sandstone, gray, thin-bedded, cross-bedded	2
60	Covered interval	7
59	Sandstone, greenish gray, glauconitic, fine-grained, calcareous, thin-bedded	2
58	Covered interval, probably siltstone	13
57	Sandstone, green, blue gray, glauconitic, fine-grained, calcareous, fractured	8
56	Siltstone, blue gray	11
55	Sandstone, green, glauconitic, fine to medium-grained, very hard	1.5
54	Siltstone, green, glauconitic, blocky	13
53	Sandstone, blue gray, weathering green, fine-grained, calcareous, hard, massive	2
52	Siltstone, gray green, glauconitic, blocky	2
51	Sandstone, gray, brown, glauconitic, calcareous, plant fragments	2
50	Siltstone, gray green, glauconitic	10
49	Sandstone, blue gray, weathering green, calcareous, very hard, blocky	2
48	Siltstone, gray green, glauconitic	7
47	Sandstone, salt-and-pepper, calcareous, thin-bedded, cross-bedded, ledge-former	16
46	Siltstone, mainly green, glauconitic, some blue gray, blocky, fractured	47
45	Sandstone, gray, green, weathering brown, very hard, plant fragments	3
44	Covered interval	2
43	Siltstone, gray, black, weathering blue gray, brown; contains Naiad, sp. nov.?, *Pisidium?*, *Corbicula?*, *Campeloma* sp., *Lioplacodes* sp., *Hydrobia?*, *Amnicola?*, *Goniobasis*, 2 species, *Physa* sp., fish tooth and bone fragments	3
42	Covered interval	7
41	Siltstone, brown, green, weathering brown, gray, glauconitic	4
40	Porcellanite, blue gray, banded	3
39	Covered interval, probably siltstone	13
38	Siltstone, green, glauconitic, grades locally to a blue-gray, calcareous sandstone, fractured	2
37	Covered interval	8
36	Sandstone, green, brown, glauconitic	6
35	Porcellanite, blue, green, splintery fracture, banded with white	6
34	Siltstone, green, glauconitic	12
33	Siltstone and fine-grained sandstone interbedded, green, glauconitic, calcareous	11
32	Sandstone, salt-and-pepper, calcareous, fractured	3
31	Siltstone, blue gray, black, blocky, fractured, plant fragments	11
30	Sandstone, salt-and-pepper, medium-grained, thin-bedded, calcareous	2.5
29	Siltstone, blue gray, blocky, fractured	16
28	Sandstone, white, medium-grained with interbedded black carbonaceous siltstone, plant fragments	2
27	Siltstone, green, glauconitic	6
26	Siltstone and fine-grained sandstone, interbedded, green, glauconitic, calcareous, blocky, fractured	8
25	Sandstone, blue gray, fine-grained, calcareous, contains fossil wood and plant fragments	2
24	Siltstone, green, glauconitic; blocky, calcareous, with thin lenses of green, glauconitic sandstone; grading to gray, blue-gray, and black siltstone. A black, carbonaceous siltstone, 24 feet thick, at the bottom of the interval contains plant fragments and fossil wood	121
23	Sandstone, green, weathering brown, glauconitic, calcareous	1
22	Siltstone, green, blue gray, glauconitic, blocky, fractured	7
21	Sandstone, salt-and-pepper, thin-bedded, calcareous	3
20	Covered interval	5
19	Siltstone, blue gray, calcareous, contains plant fragments, *Campeloma*, and undetermined gastropods	2
18	Sandstone, salt-and-pepper, coarse-grained, very thin-bedded, calcareous	14
17	Shale, blue gray, fractured	7.5

Unit No.		Thickness (Feet)
16	Sandstone, green, glauconitic, medium-grained	2
15	Siltstone, gray, green, blue gray, glauconitic, blocky, grades to green, glauconitic shale at bottom of interval	32
14	Sandstone, salt-and-pepper, slightly calcareous	2
13	Siltstone, gray green, glauconitic, fractured	8
12	Sandstone, salt-and-pepper, weathers gray to tan, calcareous, fractured	4.5
11	Siltstone, blue gray, brown, blocky	11
10	Limestone, blue gray, hard, fossiliferous, grades locally to calcareous siltstone; contains *Discus* sp. nov.?, *Physa* sp., *Gyraulus* sp., *Campeloma* sp., *Valvata* sp., *Pisidium* sp., *Sphaerium* sp.	2
9	Limestone, blue gray, weathers brown, shaly, contains *Discus* sp. nov.?, *Gyraulus* sp., *Physa* sp., *Amnicola* sp., *Campeloma*, 2 species, *Lioplacodes* sp., *Goniobasis* sp., *Pyrgulifera humerosa* Meek, one small specimen, *Sphaerium* sp., fish tooth, abundant plant fragments	2
8	Siltstone and shale interbedded, blue gray, black; 3.5 feet of green, glauconitic siltstone at base	22
7	Sandstone, salt-and-pepper, coarse-grained, massive at base, remainder thin-bedded and cross-bedded, ridge-former	22
6	Shale, dark gray to black, weathering gray, calcareous, contains *Physa* sp., *Campeloma* sp., *Lioplacodes* sp., *Amnicola?*, carinate gastropod	24
5	Sandstone, salt-and-pepper, calcareous	4
4	Shale and siltstone, blue gray, black, blocky, contains plant fragments	15
3	Sandstone, salt-and-pepper, medium-grained, calcareous, thin-bedded. Top 0.5 to 1.0 foot very calcareous and grades locally to limestone	5
2	Shale, gray, green, glauconitic	25
1	Sandstone, salt-and-pepper, coarse-grained, calcareous, thin-bedded, cross-bedded, jointing conspicuous, ledge former	22
	Total thickness of Aspen	1307.5
	Bear River formation	

Discussion

The Cretaceous formations in the Willow Creek area can be identified readily in the field by their lithologic characteristics. These can be summarized as follows: lower part of Frontier formation (Upper Cretaceous), gray to buff shale and sandstone, coal beds; Aspen formation (Lower Cretaceous), salt-and-pepper sandstone, glauconitic siltstones and porcellanites; Bear River formation (Lower Cretaceous) red, purple, maroon siltstones, some limestone. No unconformities were observed in the area.

The abrupt change from the purplish beds that the writers assign to the Gannett group in Willow Creek, to the green siltstones that the writers assign to the basal Bear River, makes a convenient contact between the two formations. The Bear River-Aspen boundary is placed above the thick, dark, splintery shale of Bear River aspect (Bear River section, unit 23) and below the first salt-and-pepper sandstone (Aspen section, unit 1). This contact is satisfactory on lithologic grounds since the salt-and-pepper sandstones seem more nearly related to Aspen lithology than Bear River. It is also acceptable from a paleontologic standpoint. The writers place the top of the Bear River lower than that of Dobrovolny (1941, p. 439) mainly because they believe the lower beds of their Aspen section to be more closely related to that formation than to the Bear River. The Aspen-Frontier contact, at least in the Willow Creek area, is so striking that it need not be discussed here.

Assuming that these contacts are correctly placed, the Bear River formation in Willow Creek has a total thickness of 541 feet, the Aspen 1307 feet. Reeside (personal communication) points out that the Aspen sequence in Willow Creek is very similar to that between Cokeville and Sage Junction, Wyoming, to which Rubey is giving a manuscript name because of uncertainty as to the level of the highest exposures. Some of the nonmarine fossils from the latter sequence have been described by Yen (1951, p. 14–17); their relationships with the faunas of our section are discussed later in this paper.

Porcellanite beds found in the area are limited to the Aspen formation and are excellent marker beds for field mapping in this area. The porcellanite is a vitrified tuff with petrological characteristics of rhyolite. Por-

cellanite is a varicolored, hard, brittle rock often interbedded with tuffaceous or porcellaneous siltstones. It is usually well bedded and may be spotted or banded.

The tuff in this region was probably deposited in fresh-water lakes; it often contains fossil ferns and fossil wood. The porcellanite occurs over 63 feet of section and suggests volcanic activity over a considerable period of time. It must be emphasized that the presence of porcellanite as a criterion for recognition of the Aspen is local and limited. Reeside (personal communication) points out that Veatch included porcellanite well up in his Frontier and that Love does so all over Wyoming. Veatch also included porcellanites locally in his Bear River. Rubey and others prefer to put all porcellanites in the Aspen or Mowry without regard to the intermediate beds; *i.e.*, they exclude all porcellanites from the Frontier or Bear River. Each side can make a case for its point of view.

Paleontology

Bear River Faunas

Fossils are found in 14 of the units of the Bear River section in Willow Creek. Those containing only plant fragments may be discounted as undiagnostic, and attention may be concentrated on units 16 and 19 of the section which contain abundant invertebrates. The distribution of genera and species in all fossiliferous units is shown in Tables 1 and 2. Identifications are provisional as the literature and collections necessary for precise identifications are not available.

Unit 16 undoubtedly contains a fresh-water assemblage. The only doubtful element is *Pyrgulifera humerosa* Meek which has been found in brackish-water assemblages. Its presence in great numbers, together with abundant Naiades, suggests that *Pyrgulifera humerosa* was a fresh-water gastropod; Reeside (personal communication) reports that he has frequently found this and other species of *Pyrgulifera* with only fresh-water associates and in an abundance that suggested original occurrence. *Pyrgulifera* may have been remarkably euryhaline, but the writers prefer to think of its occurrence in brackish-water or marine assemblages as due to transportation.

The Naiades are archaic forms in which the beak sculpture extends far beyond the earlier stages of the shell. Their generic position has not been exactly ascertained, and three of them may prove to be new. No specimens of *Ostrea haydeni* White or of *Modiolus pealei* White were found in this bed.

Unit 19 consists almost entirely of the broken shells of *Ostrea haydeni* and *Modiolus pealei*. No specimens of the species listed for unit 16 were found in unit 19. It is emphasized that units 16 and 19 are separated by more than 69 feet of sediments and that the two faunas are distinct and separate. They may occur together in other areas, but in Willow Creek area the two faunas are always separate.

In summary, the Bear River formation in the Willow Creek area is a series of near-shore, brackish- and fresh-water sediments, with frequent fluctuations of shore line and source material. Two distinct faunas are found in it, one fresh-water, the other brackish water. The formation is characterized by the abundance of *Pyrgulifera humerosa* Meek.

Examination of the section and the position of the faunas in it shows that fossil invertebrates are concentrated in two units (16, 19) of the section and that the remainder of the section consists of alternating coarse and fine clastics, with a few coal beds (units 8, 11). Sedimentation proceeded for a long time in the Willow Creek area before abundant invertebrates invaded it. After the accumulation of 373 feet of sediments a fresh-water fauna existed for a short time (unit 16). Accumulation of sediments to a thickness of 70 feet proceeded before another fauna appeared (unit 19); the remainder of the section is barren of fossils. Any conclusions on the basis of fossils as to the age of the Bear River formation in this area will therefore be valid for the upper 166 feet of the section. By inference, the lower 373 feet may be considered the same age, but there is no proof that they belong to the same division of Cretaceous time.

Aspen Faunas

Fossils are found in 25 units of the Willow Creek section. Those units containing only

TABLE 1.—COMPARISON OF BEAR RIVER AND ASPEN MARINE AND BRACKISH-WATER FAUNAS

	Bear River							*Aspen*	
	6[1]	*9*	*10*	*12*	*18*	*19*	*20*	*64*	*76*
Plants									
Fucoids	x	x	x	x	x	..	x	..	x
Plant fragments	..	..	..	x	..	..	..	..	..
Pelecypoda									
Ostrea cf. *haydeni*	..	..	..	..	..	x	..	..	..
Modiolus cf. *pealei*	..	..	..	..	..	x	..	..	..
Modiolus sp.	..	..	..	..	..	..	..	x	x
Corbula? sp.	..	..	..	..	..	..	..	x	..
C. cf. *engelmanni*	..	..	..	..	..	..	..	x	..
Glycymeris?	..	..	..	..	..	..	..	x	..
Myalina?	..	..	..	..	..	..	..	..	x
Macoma?	..	..	..	..	..	..	..	..	x
Arca sp.	..	..	..	..	..	..	..	..	x
Pecten? (fragment)	..	..	..	..	..	..	..	..	x
Pelecypods undet.	..	..	..	..	..	..	..	x	..
Gastropoda									
Gastropod undet.	..	..	..	..	..	..	..	..	x
Pyrgulifera?	..	..	..	..	..	..	..	x	..
Cerithium?	..	..	..	..	..	..	..	x	..
Rhytophorus?	..	..	..	..	..	..	..	x	..
Bithynella?	..	..	..	..	..	..	..	x	..
Arthropoda									
Ostracode	..	..	..	..	..	..	..	x	..
Crustacean claw?	..	..	..	..	..	..	..	..	x

[1] Numbers of units in measured section

fossil wood and plant fragments may again be discounted, leaving 9 units which merit discussion. Distribution of genera and species is shown in Tables 1 and 2.

The first fauna of any importance encountered in the Aspen is that of unit 6, between the third and fourth salt-and-pepper sandstones. It is an exclusively fresh-water fauna in which the only puzzling element is a carinate gastropod which, however, is not a *Pyrgulifera*.

The fauna of unit 9 is also a fresh-water one, and it contains in addition a land snail, identified as *Discus* sp., probably a new species. In spite of diligent search, only one specimen of *Pyrgulifera humerosa* Meek was found here. When this isolated occurrence is compared with the great abundance of *P. humerosa* in the Bear River section, its importance with respect to the age of the Aspen and the placing of the Bear River-Aspen contact appears slight.

Unit 10 contains a fauna of the same character as that of unit 9 except that two genera, *Valvata* and *Pisidium*, make their first appearance in the section. *Pyrgulifera*, *Amnicola*, and *Goniobasis* are not represented.

Unit 19 contains only poorly preserved gastropods, only one of which, *Campeloma*, could be identified even generically. The presence of *Campeloma* indicates that this is also a fresh-water unit.

Unit 43 is also of fresh-water origin, but the presence of *Corbicula* suggests brackish conditions for part of the time of its accumulation.

Unit 64 is definitely marine. The presence of a *Corbula*, very like *C. engelmanni* of the Bear River, is rather unexpected, but further study may show it to differ specifically from the Bear River form.

The fossils of unit 71 are freshwater. At this horizon, a new element has been introduced into the fauna, a species of *Lymnaea*. This genus has not been found in the underlying beds of either the Aspen or the Bear

River. On the other hand, unit 76 is marine; the genera represented are marine, and the assemblage is a near-shore one. Unit 78, although it contains only ferns, probably indicates a return to fresh-water conditions, as do the plant fragments and fossil wood of units 77, 78, 92, and 105.

Examination of the faunal lists shows that the faunas and floras of the Aspen formation are both rich and varied. They show that the area of Willow Creek was at first a fresh-water lake in which 5 distinct faunas (units 6, 9, 10, and 43) succeeded each other with long interruptions during which sediments barren of fossils were deposited. Glauconite in units 46, 48, 50, 51, 52, 54, 55, 57, and 59 implies marine origin of the sediments, but conditions were apparently unfavorable for the establishment of faunas. Some time later, a marine fauna invaded the region, and its fossils are preserved in unit 64. The sea retreated, and another body of fresh water occupied the area (unit 71). The intermittent deposition of tuff (porcellanite), starting with unit 72, probably killed off the fresh-water mollusks by rapid accumulation of siliceous muds. Sedimentation continued, but conditions favorable for the existence of fresh-water mollusks apparently were not restored before the close of the Aspen.

The faunas of the Aspen of Willow Creek are quite different from most of those recorded previously from other regions. In fact, published accounts of the Aspen give the impression that it contains very few fresh-water fossils and an abundance of marine ones. Veatch (1907, p. 64–65) mentions no fossils. Reeside and Weymouth (1931, p. 4–5) record fish scales and a large marine fauna; some of their ammonite identi-

TABLE 2.—COMPARISON OF BEAR RIVER AND ASPEN NON-MARINE FAUNAS

	Bear River						*Aspen*						
	1	*5*	*7*	*8*	*11*	*16*	*6*	*9*	*10*	*19*	*43*	*71*	*78*
Plants													
Plant fragments	x	x	x	..	..	..	..	x	..	x	..	..	..
Fossil ferns	..	..	..	..	..	..	..	..	..	..	..	..	x
Coal	..	..	..	x	x	..	..	..	..	..	..	..	..
Pelecypoda													
"*Unio*" cf. *vetustus*	..	..	..	..	..	x	..	..	..	..	..	..	..
Naiad, sp. nov.?	..	..	..	..	..	..	..	..	..	..	x	..	..
Naiades undet.	..	..	..	..	..	x	..	..	..	..	..	..	..
Corbicula?	..	..	..	..	..	..	..	..	..	..	x	..	..
Corbula cf. *engelmanni*	..	..	..	..	..	x	..	..	..	..	..	..	..
Sphaerium sp.	..	..	..	..	..	..	..	x	x	..	..	..	..
Pisidium sp.	..	..	..	..	..	..	..	..	x	..	x	..	..
Gastropoda													
Pyrgulifera humerosa	..	..	..	..	..	x	..	x	..	..	..	..	..
Campeloma sp.	..	..	..	..	..	..	x	x	x	x	x	x	..
C. cf. *macrospira*	..	..	..	..	..	x	..	..	..	..	..	..	..
Lioplacodes sp.	..	..	..	..	..	x	x	x	..	..	x	x	..
Goniobasis spp.	..	..	..	..	..	x	..	x	..	..	x	x	..
Charydrobia sp.	..	..	..	..	..	x	..	..	..	..	..	..	..
Hydrobia sp.	..	..	..	..	..	x	..	..	..	..	x	..	..
Valvata sp.	..	..	..	..	..	x	..	..	x	..	..	..	..
Amnicola (?) sp.	..	..	..	..	..	x	x	x	..	..	x	..	..
Physa sp.	..	..	..	..	..	..	x	x	x	..	x	..	..
Gyraulus sp.	..	..	..	..	..	..	..	x	x	..	..	..	..
Lymnaea sp.	..	..	..	..	..	..	..	..	..	..	..	x	..
Discus sp. nov.?	..	..	..	..	..	..	..	x	x	..	..	..	..
Gastropods undet.	..	..	..	x	..	..	..	x	..	x	..	x	..
Fish remains	..	..	..	..	..	..	..	..	x	..	x	..	..

fications were changed later by Cobban and Reeside (1951). Dobrovolny (1941, p. 439–441) lists plant fragments in the upper part of his unit 18, ganoid scales abundant in his unit 13. In the part of the Aspen which he includes in the Bear River (Dobrovolny, 1941, p. 437), he records a "gastropod, possibly Pyrgulifera", in his unit 10 and plant remains in units 8 and 9, but he apparently failed to find the rich faunas here recorded. Yen (1951, 14–17) has described nonmarine faunas from the Leeds Creek area near Cokeville, Wyoming, which Reeside (personal communication) considers Aspen in age. At first glance, Yen's list appears entirely different from the Aspen list of this paper (Table 2), but it is entirely possible that they may contain some identical species which lack of comparative material forbade the writers to identify specifically or to describe as new.

No conclusions as to age can be made from the assemblages studied in Willow Creek area. On the one hand, the marine faunas contain no ammonites, and on the other the fresh-water Mollusca cannot be compared with similar assemblages of known age except the Leeds Creek fauna. However, the Aspen faunas of this area differ markedly from those of the Bear River, enough to be distinguished from them without difficulty.

Discussion

Formation Boundaries

The boundary between the Gannett and the Bear River formations can be established on lithologic grounds; no paleontologic evidence is available in the Willow Creek area. The boundary between the Bear River and Aspen formations is placed between the uppermost thick shales of the Bear River section and the first salt-and-pepper sandstone overlying them; this boundary appears logical both on lithologic and paleontologic grounds.

"Mixed Faunas"

Published lists of the fauna of the Bear River (Henderson, 1935, p. 25–26; Dobrovolny, 1941, p. 436–38) have a peculiar character—brackish-water or marine and fresh-water forms are listed together, as if they occurred naturally side by side in the same beds. A situation of this sort, when it exists, may be explained: (1) by washing in of dead shells of fresh-water forms into a marine environment; (2) by assuming that the "mixed faunas" are the result of reworking of two or more layers whose fossils have been mixed; (3) by assuming that a fresh-water habitat has been invaded by the sea, and that marine forms became established before the fresh-water fauna was covered by sediments. "Mixed lists" as distinguished from "mixed faunas" may be due to the fact that collecting was not sufficiently careful and that fossils from several units have been lumped together. Mixed lists from the Bear River formation in Willow Creek area can be explained in this way, for the sections and collections show that the brackish-water unit is separated from the fresh-water one by some 70 feet of sediments barren of fossils.

In other areas, Reeside (personal communication) has observed a real association of *Unio* with *Brachydontes* which he feels must be explained as a death-assemblage rather than a life-assemblage. The writers fully agree with this explanation for undoubted cases of real associations of fresh-water and brackish-water forms, but they emphasize that such an explanation is unnecessary for the Willow Creek assemblages.

Nature of the Aspen Faunas

The Aspen formation in the Willow Creek area contains both marine and nonmarine faunas at 25 separate horizons. The nonmarine faunas are found throughout the formation; the marine ones are concentrated toward the top, but nonmarine faunas alternate with them. These assemblages differ from those of the Bear River, and the occurrence of one specimen of *Pyrgulifera* (possibly a derived fossil) in two of the units is considered insufficient evidence to justify inclusion of these beds in the Bear River formation. The writers are all the more inclined to minimize the importance of *Pyrgulifera* in defining the Bear River-Aspen boundary since Reeside (personal communication) states that a species of that genus, not *P. humerosa* according to Yen, occurs in beds assigned to the Aspen near Old

Cumberland, southeast of Kemmerer, Wyoming, associated with such forms as *Unio belliplicatus*, *U. vetustus*, and *Campeloma macrospira*.

Age of the Bear River and Aspen Formations

Yen (1952, p. 761–62) contends that, on the basis of its fauna at the type locality and elsewhere, the Bear River formation should be considered Cenomanian. On the other hand, Cobban and Reeside (1951) have shown that certain Aspen faunas are Albian, and they have assigned the Aspen to the Albian in their correlation charts (Cobban and Reeside, 1952, Pl. 1, cols. 63, 64, 66). These statements appear irreconcilable, but they are not as contradictory as they seem. The ammonite faunas, on which Cobban and Reeside base their determination, contain *Neogastroplites*, known hitherto only from the upper Albian of northern Canada. The difference of opinion reduces itself, therefore, to upper Albian versus Cenomanian but with the difficulty that the Aspen is considered upper Albian by Cobban and Reeside, and the underlying Bear River is called Cenomanian by Yen.

Consideration of the Willow Creek section and its faunas, discussed in this paper, suggested that the conflicting age assignments might be due to complex intertonguing between the two formations. Reeside has dissuaded the writers from presenting such a solution because he has evidence in his possession which militates so strongly against it that he considers the solution untenable. Since he and Cobban are preparing a paper on the subject, the present discussion is confined to presentation of data from the immediate area investigated. Here, the characteristic fauna of the Bear River formation is found only in the upper third of the section. Strictly speaking, only the upper third of the section can be dated on the basis of faunas. The section is thin (500 to 5000 feet; Wilmarth, 1938, p. 134) compared with the thickness of the Bear River elsewhere. In the Aspen of Willow Creek, no diagnostic ammonites have been found. These beds are identified as Aspen on the basis of stratigraphic position and lithology; there is no direct paleontologic evidence of their age except for the overlying beds identified as Frontier. The comparison with Yen's Leeds Creek fauna is inconclusive.

References Cited

Cobban, W. A., and Reeside, J. B., Jr., 1951, Lower Cretaceous Ammonites in Colorado, Wyoming, and Montana: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 1892–1893.

—— 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geol. Soc. America Bull., v. 63, p. 1011–1044, 2 figs., 1 pl.

Dobrovolny, Ernest, 1941, Jurassic and Cretaceous strata of the Camp Davis area, Wyoming: Mich. Acad. Sci. Arts and Letters, Papers, v. 26, p. 429–443.

Henderson, Junius, 1935, Fossil non-marine Mollusca of North America: Geol. Soc. America Spec. Paper no. 3, 313 p.

Reeside, John B., Jr., and Weymouth, A. Allen, 1931, Mollusks from the Aspen shale (Cretaceous) of Southwestern Wyoming: U. S. Nat. Mus. Proc., v. 78, Art. 17, 24 pages, 3 pls.

Veatch, A. C., 1907, Geography and geology of a portion of southwestern Wyoming, with special reference to coal and oil: U. S. Geol. Survey Prof. Paper 56, 178 pages.

Wilmarth, M. Grace, 1938, Lexicon of geologic names of the United States: U. S. Geol. Survey Bull. 896, 2396 pages.

Yen, Teng-Chien, 1951, Fresh-water mollusks of Cretaceous age from Montana and Wyoming: U. S. Geol. Survey Prof. Paper 233-A, 20 pages, pls. 1, 2.

—— 1952, Age of the Bear River formation, Wyoming: Geol. Soc. America Bull., v. 63, p. 757–763.

The Ohio State University, Columbus, Ohio; General Petroleum Corporation, Bakersfield, California.

Manuscript Received by the Secretary of the Society, February 2, 1953

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 327-336, 3 FIGS. APRIL 1954

FORAMINIFERAL POPULATIONS IN THE GRAYSON MARL

By Claude C. Albritton, Jr., William W. Schell, Charles S. Hill, and John R. Puryear

Abstract

At Grayson Bluff in Denton County, Texas, the Grayson formation (Cretaceous) is 78 feet thick. It is divisible into four lithologic units: a lower marl, lower clay, upper marl, and upper clay. Each unit contains tests of Foraminifera in astonishing numbers that range from 1500 to more than 100,000/cm³.

Twenty-two samples collected from as many horizons in the Grayson were analyzed according to their content of foraminiferal tests, classified by genera and families. The Lituolidae are the predominant benthonic family in the upper clay. In the lower clay the Bulminidae generally outnumber the combined Anomalinidae, Rotaliidae, and Lagenidae, while in both marl units the converse is the case.

Lowman has shown that different families of Foraminifera predominate at different depths beneath the present Gulf of Mexico. Comparing the microfaunal facies of the Grayson with those described by him, it may be inferred that the lower two units of the Grayson were deposited in deepening waters, while the upper two were deposited in shoaling waters. This is compatible with the chronicle for the late Comanchean as known from studies of lithology, megafossils, and geologic structure. Similar analyses in other parts of the Coastal Plain might establish the order of reliability of foraminiferal populations as indicators of fluctuations in depth around the borders of the ancient Gulf of Mexico.

CONTENTS

TEXT

	Page
Depth facies of benthonic Foraminifera	327
Late Comanchean history in the Denton County area	328
Grayson formation at Grayson Bluff	331
Lithology and thickness	331
Foraminifera	331
General considerations	331
Planktonic Foraminifera	332
Benthonic Foraminifera	334
Microfaunal facies of benthonic Foraminifera	334
Comparison with Recent depth facies	335
Historical synthesis	336
References cited	336

ILLUSTRATIONS

Figure	Page
1.—Relative abundance of foraminiferal tests in different parts of Grayson marl	329
2.—Composite benthonic populations in four lithologic subdivisions of the Grayson marl	333
3.—Facies of benthonic Foraminifera in the Grayson marl	335

Depth Facies of Benthonic Foraminifera

During the past decade much has been learned regarding the distribution of Recent Foraminifera over the bottom of the Gulf of Mexico. Off the shores of Texas and Louisiana Phleger found six depth facies of benthonic foraminifers between the approximate limits of 10 and 1100 fathoms. Each of these was defined largely on the overlapping ranges of species. Lowman had previously demonstrated that in these same waters depth facies could be defined using taxonomic categories above the rank of species. Thus he was able to distinguish between the populations of the inner neritic, mid-neritic, outer neritic, and inner bathyal levels according to differences in the predominant foraminiferal genera and families. As investigations in this area are continued, the findings of the pioneers are likely to be refined

and modified. Meanwhile it seems well established that different kinds of Foraminifera inhabit bottoms at different depths, although temperature of water rather than depth may be the more fundamental control.

The present Gulf of Mexico is a remnant of a body of water that was more extensive during parts of the Mesozoic and Cenozoic eras. Well cuttings and exposures in the Coastal Plain indicate that sediments laid down in this ancient Gulf abound in the tests of foraminifers at many horizons. Quantitative studies of foraminiferal populations and their sequences in ancient rocks, followed by comparisons of ancient assemblages with modern ones, might lead to increased knowledge of the fluctuations in depth around the ancient Gulf of Mexico.

Admittedly it is not a simple matter to draw valid inferences as to the conditions of origin of ancient rocks on the basis of their content of Foraminifera. There is, for example, the question of what fraction of some microfauna actually lived at the site of burial as compared with the numbers and kinds of tests that were transported there. Problems of a different kind arise from taxonomic considerations. Depending on whether the paleontologist's concept of species be broad or narrow, a fossil fauna may seem to have many or few species in common with recent populations; and depth zones based on the living animals may in turn seem to have more or less applicability to ancient terranes. In this regard the difficulty increases with the age of the rock. To deposits of Mesozoic age Phleger's depth zones based on living species will hardly apply—not even with the broadest definition of species. The question then arises as to whether Lowman's zones, based on genera and families, are to be found in rocks that were formed a hundred million or more years ago. In rocks so old there will almost invariably be some genera that have become extinct and others whose affinities with one or another family are in doubt.

In spite of these and other complications, it seems desirable to test the feasibility of using depth facies of Recent foraminifers in connection with historical studies of ancient rocks in the Gulf Coastal Plain. There are doubtless many stratigraphic sections that would be suitable for this purpose, for there are but two important prerequisites: (1) the rocks should contain abundant Foraminifera, which are presumably of the same age as the matrix, and which bear at least a familial resemblance to living assemblages; (2) there should be local evidence for changing depths of water in the course of deposition, and these changes should be broadly decipherable on grounds other than the foraminiferal content itself. Interpretations based on successions of foraminiferal populations could be compared with interpretations based on lithology, primary structures, and megafossils. If in a sufficient number of cases the two lines of inference turned out to be the same or at least compatible, foraminiferal populations might become useful as independent indicators of fluctuations in depth.

Late Comanchean History in the Denton County Area

A section that fairly well satisfies these prerequisites is exposed at Grayson Bluff, 3.7 miles N. 51° E. of Roanoke in Denton County, Texas. The column includes in ascending order the upper part of the Main Street limestone, the entire Grayson marl, an eroded remnant of the Buda limestone, and the basal layers of the Woodbine sand (Fig. 1). All these rocks are of Cretaceous age. The Woodbine is the basal unit of the Gulf Series, and beds below it belong to the Washita group of the Comanche Series. Many geologists would draw the boundary between the Lower and Upper Cretaceous along the contact between these two series; but Cobban and Reeside (1952, Chart 10b) have recently assigned the upper part of the Washita group, beginning with the equivalent of the Grayson marl, to the Upper Cretaceous. So far as this study is concerned it is sufficient to say that the rocks at Grayson Bluff lie near the boundary between the Upper and Lower Cretaceous.

The principal events in the geologic history of this area may be inferred from the lithology, megafossils, and structural features visible at the outcrop. Sediments of the Main Street, Grayson, and Buda formations were laid down beneath the ancient Gulf of Mexico. The sea grew shallower toward the close of Comanchean time, and after the Buda limestone had been deposited the waters withdrew. Streams cut

COLUMN INSOLUBLE FAMILIES OF FORAMINIFERA FORAMINIFERAL TESTS

FIGURE 1.—RELATIVE ABUNDANCE OF FORAMINIFERAL TESTS IN DIFFERENT PARTS OF GRAYSON MARL

In center: by families, according to percentage of total population. In column at right, according to number of tests/cm³. In column at left Km = Main Street limestone, Kg = Grayson marl, Kb = Buda limestone, and Kw = Woodbine sand.

valleys through the Buda and into the Grayson marl. In time the land began to subside, and the complex of fluvial, deltaic, lagoonal, and littoral deposits of the Woodbine formation covered hills and valleys with layers of sand and clay.

The evidence for this sequence of events is as follows. A marine origin for strata below the Woodbine is indicated by the common occurrence of ammonites, scallops, bryozoans, and brachiopods—to mention but a few of the many kinds of fossils for which Grayson Bluff has become well known to collectors. *Kingena wacoensis* (Roemer), a terebratulid brachiopod, makes up whole layers in the Main Street limestone. The ram's horn oyster, *Exogyra arietina* Roemer, weathers in great numbers from along the boundary between the Main Street and the Grayson. *Turrilites*, *Stoliczkaia*, and *Engonoceras* are fairly common ammonites in the upper part of the Grayson, where they are associated with many grypheate and pectinate pelecypods. Fossils in these beds are exquisitely preserved; many of the scallop shells retain their fragile auricles, and some the traces of original color patterns. From the Buda limestone at Grayson Bluff, Adkins and Lozo have taken specimens of the ammonite *Budaiceras* and the clam *Exogyra clarki* Shattuck (Bailey *et al.*, 1945, p. 175).

Preservation of fossils within the Buda differs from that in the beds below. A large percentage of the shells in the Grayson and Main Street are entire. Many of the oysters in the upper Grayson are encrusted, inside and out, with tiny tubes constructed by marine worms, or by colonies of lacy Bryozoa. Preservation of these delicate fossils argues for slow accumulation of sediment in quiet water. By contrast, the Buda contains few whole shells but many rounded fragments. Its texture, at least locally, is coquinitic, and it is in essence a granular rock made of calcareous particles. The shells within it are evidently not reworked from the Grayson, because many of them are unlike those found in the section immediately below. Presumably then the Buda was laid down on bottoms that were frequently agitated by waves and currents, the motion of which caused many of the sea shells to be broken and ground into particles ranging downward to the size of sand grains. Assuming that the base of wave and current action remained essentially the same throughout the closing interval of Washita time, the differences in lithology between the Buda and Grayson might be explained in terms of progressively shoaling waters.

Support for this hypothesis is afforded by certain structural features along the base of the Woodbine indicating that the sea floor actually emerged after the Buda had formed. Slabs of hard Buda limestone that litter the upper slopes around Grayson Bluff are nearly everywhere perforated by tortuous and irregularly branching fillings of a sandy ferruginous material identical with that found along the base of the Woodbine. These fillings range up to 2 inches in diameter. In places they seem to follow cracks in the rock, though in general they do not seem to be guided by planes of structural weakness. They appear to occupy solution channels, such as may form in limestone by the downward passage of ground water, and so to record the effects of subaerial weathering. This interpretation is consistent with the report of a fossil soil at the base of the Woodbine to the north of this area in Cooke County, Texas (Bailey *et al.*, 1945, p. 183). Southward in Tarrant County Dodge (1952, p. 70–71) found what are either root fillings or desiccation cracks filled with basal Woodbine sand and penetrating the upper part of the Grayson marl. At the locality described by Dodge the Buda is missing, as indeed it is from most of the outcrop area in northern Texas. The surface of the unconformity below the Woodbine is thus irregular, with a relief of several tens of feet. Such a surface must have been sculptured by streams.

Assuming this to be the correct order of events, one might expect to find evidence for shoaling in the changing character of the microfauna within the rocks of the upper Washita group. Gayle Scott (1940), in his memorable address on the ecology of Cretaceous ammonites, concluded that the Main Street with its abundant turrilitid cephalopods was probably deposited in the infraneritic zone at depths between 20 and 100 fathoms. Applying Scott's bathymetric criteria to the upper Grayson, in

which the compressed shells of *Engonoceras* are locally mingled with abundant thick-shelled oysters, there is at least the suggestion that these beds may have been deposited in the shallower epineritic zone at depths between 5 and 20 fathoms. If so, then the shoaling of the Washita seas that foreshadowed the emergence of this area may have begun with the deposition of the upper Grayson marl. Do the Foraminifera in the Grayson beds indicate that such was the case?

Grayson Formation at Grayson Bluff

Lithology and Thickness

The Grayson formation at the bluff that carries its name in Denton County is 78 feet thick. It is divisible into four lithologic units, here designated informally as lower marl, lower clay, upper marl, and upper clay. Essential features of lithology and thickness are as follows:

Stratigraphic section measured at Grayson Bluff, Denton County, Texas

	Thickness (Feet)
Gulf series	
Woodbine formation—	
7. Friable ferruginous sandstone.....	10+
——— Unconformity ———	
Comanche series	
Buda limestone—	
6. Coquinitic limestone.....	0–4
Grayson formation—	
5. Upper clay. Greenish-gray clay containing small *Exogyra* and *Plicatula*; poorly exposed.....	15.00
4. Upper marl. Marl with interbedded marly limestone and clay; colors range from yellowish gray to greenish gray. Contains abundant pelecypods (*Gryphaea*, *Plicatula*, and *Pecten*) and both gastropods and echinoids in considerable numbers; ammonites present but not common.	21.30
——— Disconformity ———	
3. Lower clay. Clay that is predominantly greenish- or yellowish gray toward bottom, becoming pale yellowish green toward top. Contains few megafossils; small and possibly dwarfed *Plicatula* locally present....	24.00
2. Lower marl. Yellowish-gray marl grading upward into less calcareous greenish-gray marl. Contains *Exogyra arietina* toward base and scattered large *Gryphaea* higher in section.....	18.25
Total thickness of Grayson formation.....	78.55
Main Street limestone—	
1. Shelly limestone becoming marly toward top where it grades into lower marl of Grayson formation; base not exposed.....	10.00+

Foraminifera

General considerations.—The marl and clay of the Grayson formation contain the tests of small Foraminifera in great numbers. These were classified by Tappan (1940) who identified 90 species representing 45 genera and 16 families. With the aid of this excellent report it was possible to make quantitative studies of the foraminiferal populations with a minimum of time and effort spent on identification.

Our procedure was as follows. Twenty-two samples were collected from as many different horizons in the Grayson ranging from the bottom of the formation to the limits of exposure near the top. Each sample represents about 6 inches of vertical section. In the lower part of the formation where the rock is fairly homogeneous, samples were taken at vertical intervals of 5.5 feet. In the upper part where there are numerous thin beds of marly limestone, samples were taken at irregular intervals in order that there might be at least one for each stratum of marl or clay between the limestone layers. The horizons at which samples were taken are indicated by dots on the insoluble residue curve of Figure 1.

Twenty-five cc. of each sample was reduced to sludge by the Campbell method as described by Hussey and Campbell (1951) and then washed through U. S. Standard seive 325 (nominal opening .044 mm.). Material retained in this seive was dried and then weighed. One twenty-fifth of the thoroughly mixed residue was then spread thinly over micropaleontological slides of the kind ruled into numbered squares. Each of the first 500 mature tests

found on the slides was identified by genus; the remaining tests were simply counted. From these data the percentage composition by genera and families and the number of tests per cc. of original sample were calculated. Figure 1 shows the variation in numbers of tests and also in percentage composition according to families throughout the lower 66 feet of the Grayson, as indicated by examination of the 22 samples.[1]

Although all parts of the Grayson formation examined could be classed as richly foraminiferal, the number of tests per unit volume of rock varies widely. The least fossiliferous material examined, a clay near the top of the upper marl unit, contained approximately 1500 tests/cm³. A sample of marl from the base of this same unit contained not less than 108,000 tests/cm³. In general the more fossiliferous rocks are also the more calcareous, but this is no more than a statistical generalization, for some clays contain more tests per unit volume than do some marls. Moreover the situation with respect to the most calcareous rocks in the section remains unknown, because even with the aid of the Campbell sample washer these harder rocks could not be broken down without breaking many of the microfossils.

Planktonic Foraminifera.—Foraminifera that were presumably planktonic are dominant in all but 4 of the 22 samples examined. In 10 samples they account for half or more of the total number of tests. Broadly speaking the percentage of planktonic forms tends to vary directly with the amount of clay and inversely with the numbers of tests per unit volume of rock. Each of the 10 samples mentioned above contains less than 45 per cent acid-soluble matter, and 6 are clays with less than 25 per cent acid-soluble matter. Eight of these samples contain less than 25,000 tests/cm³, a figure which though sufficiently large is smaller than the mean for all lithologic units of the Grayson except the upper clay.

Among the planktonic foraminifers *Globigerina*, represented by several species, is most common. It is the predominant genus in the basal 30 feet of the Grayson where it accounts for approximately 20 to 45 per cent of the entire population. At most levels above a horizon near the middle of the lower clay this genus is outranked in numbers by genera belonging to other families. However, at the base of the upper clay where the total number of tests is abnormally low, *Globigerina* accounts for 73 per cent of the total population.

Because *Globigerina* survives as a foraminifer whose floating habits are well known, the planktonic nature of its fossil species is likely to be accepted. In addition to this genus we have classified as planktonic *Gümbelina*, *Gümbelitria*, and *Gümbelitriella*, all members of the Heterohelicidae. Each of these genera is extinct, and therefore the assignment of any of them to the planktonic fraction must be based on evidence that is less direct and less probable than in the case of *Globigerina*. Cushman (1948, p. 252) suggested that *Gümbelina* may have been pelagic. Glaessner (1948, p. 193) was more emphatically of this opinion, offering the following argument in support. In certain bituminous shales of Lower Tertiary age in the Caucasus *Gümbelina* is associated with *Globigerina* and *Globorotalia* to the exclusion of other types of foraminifers. In these beds there are no benthonic megafossils. Lithologically the deposits are similar to Recent sediments in the poorly oxygenated depths of the Black Sea, which does not support aerobic benthonic life below depths of about 100 fathoms. Even if the shale accumulated on bottoms covered by stagnant poisonous water, it could still be rich in tests of *Globigerina* and *Globorotalia* which settled down from the oxygenated superficial layers of the sea in which these animals lived, formerly as at present. *Gümbelina*, which occurs with these two genera in similar numbers and states of preservation, thus probably was planktonic also. Glaessner's argument could be applied to similar shales in many other parts of the world, as for example to parts of the Eagle Ford shale in its type area around Dallas, Texas. And what is the case for *Gümbelina* is likely to be so also for the closely related genera *Gümbelitria* and *Gümbelitriella*, which tend to be more nearly globular and hence more of the shape one tends to associate with floating foraminifers.

Next to *Globigerina*, *Gümbelina* is most

[1] Crude and washed samples used in this study, together with slides of species and data sheets showing generic analyses of each sample, are on file at the Laboratory of Micropaleontology, Southern Methodist University, and are available for examination.

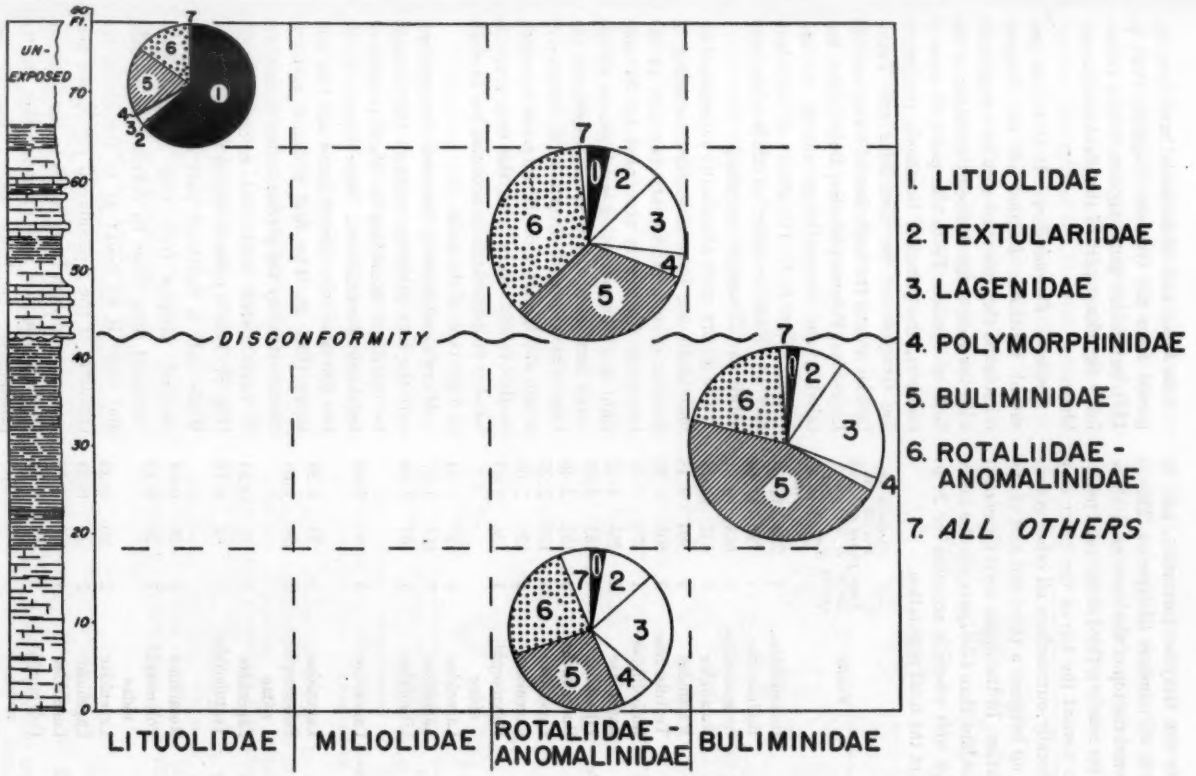

FIGURE 2.—COMPOSITE BENTHONIC POPULATIONS IN FOUR LITHOLOGIC SUBDIVISIONS OF GRAYSON MARL

Shows predominance of Lituolidae in the upper clay at top of Grayson, and of Buliminidae in lower clay unit below disconformity. In lower and upper marl units, Rotaliidae, Anomalinidae, and Lagenidae taken together outnumber Buliminidae. Percentage diagrams are arranged in vertical columns with the facies that presumably represents the shallowest water set to the left, and that representing the deepest water to the right. A miliolid facies, such as might possibly have been anticipated, apparently does not exist in the Grayson.

abundant in the Grayson formation, and in some zones it outnumbers *Globigerina*. This is the case toward the top of the lower marl where it accounts for nearly a third of the total population. Also toward the top of the lower clay *Gümbelina* locally outnumbers all other genera and makes up between a third and half of the total population. In the upper marl *Gümbelina* is more abundant than *Globigerina* in the lower 5 feet of this unit where it accounts for 20 to 30 per cent of the total population.

Genus	*Family*	*Number of species*	*Specimens in first 500 tests picked from each of 22 samples*	
			Number	*Per cent of total*
Bulimina	Buliminidae	1	739	12.05
Virgulina	Buliminidae	1	726	11.84
Anomalina	Anomalinidae	1	663	10.81
Gyroidina	Rotaliidae	1	637	10.38
Valvulineria	Rotaliidae	1	580	9.45
Textularia	Textulariidae	2	503	8.20
Neobulimina	Buliminidae	1	473	7.71
Dentalina	Lagenidae	4	253	4.12
Ammobaculites	Lituolidae	4	185	3.02
Bolivina	Buliminidae	1	152	2.48
Lagena	Lagenidae	5	139	2.27
Nodosaria	Lagenidae	6	126	2.05
Paleopolymorphina	Polymorphinidae	1	126	2.05
Lenticulina	Lagenidae	1	125	2.04
Vaginulina	Lagenidae	7	115	1.87
Haplophragmoides	Lituolidae	1	102	1.66
Pseudoglandulina	Lagenidae	3	91	1.48
Lingulina	Lagenidae	4	84	1.37
Pyrulina	Polymorphinidae	2	64	1.04
Marginulina	Lagenidae	3	51	0.83
Spiroplectammina	Textulariidae	3	48	0.78
Spirillina	Rotaliidae	1	39	0.64
Globulina	Polymorphinidae	1	26	0.42
Saracenaria	Lagenidae	2	20	0.33
Tristix	Lagenidae	2	20	0.33
Frondicularia	Lagenidae	1	16	0.26
Pseudopolymorphina	Polymorphinidae	1	15	0.24
Ramulina	Polymorphinidae	2	12	0.20
Bifarina	Buliminidae	1	4	0.07
			6,134	99.99

Schackoina and *Globorotalia* have been reported from the Grayson (Tappan, 1940, p. 123), but neither genus appears to be a numerically significant part of the planktonic assemblage.

Benthonic Foraminifera.—It is to the presumed benthonic fraction of the Grayson microfauna that one must turn for comparisons with the Recent fauna along the bottom of the Gulf of Mexico. From the point of view of numbers, the principal benthonic families in the Grasyon are the Lituolidae and Textulariidae among the agglutinated forms, and the Lagenidae, Polymorphinidae, Buliminidae, Rotaliidae, and Anomalinidae among the calcareous (Figs. 1, 2). The genera of these families are listed in order of their abundance within the 22 samples examined.

The genera most abundantly represented by individuals are least diversified according to number of species. Seventy per cent of the benthonic fraction is accounted for by only eight species representing seven genera. Of the seven families in the Grayson microfauna the Lagenidae are most diverse as to number of genera and species, although no genus belonging to this family ranks with the first seven in number of individuals or accounts for as much as 5 per cent of the total.

Microfaunal facies of benthonic Foraminifera.—If the four lithologic units of the Grayson be compared according to their content of benthonic Foraminifera, there appear to be two principal microfaunal facies and two subfacies (Fig. 2). The first principal facies is characterized by the predominance in numbers of agglutinated tests over calcareous tests (Fig. 3). This is present only in the upper clay. While only a fractional part of this unit is exposed, samples from near its base were examined three times by different individuals, and there is no doubt as to the distinctive character of the foraminiferal population here as compared with lower levels in the Grayson. *Haplophragmoides* and *Ammobaculites* are the predominant benthonic genera, together accounting for approximately 63 per cent of the benthonic fraction. While both these genera range through the exposed portion of the Grayson, they account for less than 4 per cent of

the composite benthonic population in any one of the lithologic units below the upper clay.

The second principal facies is characterized by a predominance of calcareous tests. This prevails throughout the Grayson below the base of the upper clay. Two subfacies are recognized. In the first the Buliminidae are the predominant benthonic family, and there are normally more tests belonging to this family than to the Lagenidae, Rotaliidae, and Anomalinidae combined. This subfacies predominates within the lower clay unit, where the Buliminidae account for between 18 and 24 per cent of the entire foraminiferal population and for an average of approximately 45 per cent of the benthonic fraction. Both lithologically and faunally this appears to be the most nearly homogeneous part of the Grayson formation.

In the second subfacies the sum of the tests belonging to the Lagenidae, Rotaliidae, and Anomalinidae exceeds the number of tests belonging to the Buliminidae. This subfacies persists through the entire thickness of the lower marl. It predominates in the upper marl, although there are strata near the base and in clayey units toward the top where the buliminid subfacies of the lower clay reappears.

Comparison with Recent depth facies.—In the region around the Mississippi delta Lowman found the greatest numbers of *Haplophragmoides* and *Ammobaculites* near the shore. The former is most abundant in what Scott would call the epineritic zone—on bottoms between 5 and 20 fathoms deep. The latter is most abundant in weakly brackish waters inside the shore line. At the opposite end of the depth range, the Buliminidae are the predominant family below depths around 50 fathoms in the infraneritic and inner bathyal zones. At depths between those characterized by abundant lituolids on the one hand and buliminids on the other, Lowman found highly diverse populations with many families and genera represented and locally dominated by the Lagenidae and Rotaliidae (or Anomalinidae if *Cibicides* be assigned to this family, following Cushman).

Assuming that the genera and families that enter into Lowman's definition of microfaunal facies occupied the same relative positions in regard to depth of bottom in the Cretaceous Gulf of Mexico as in the present Gulf, two inferences may be drawn. The predominance of *Haplophragmoides* and *Ammobaculites* in the upper clay indicates that this sediment was

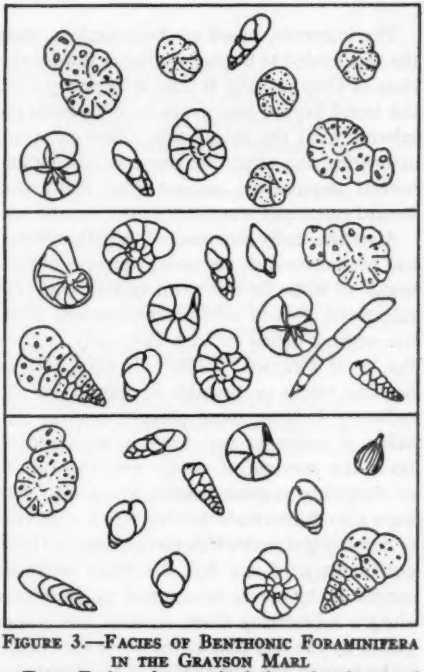

FIGURE 3.—FACIES OF BENTHONIC FORAMINIFERA IN THE GRAYSON MARL

Top.—Facies characterized by abundance of agglutinated tests (stippled) of *Haplophragmoides* and *Ammobaculites*. Characteristic of exposed part of upper clay.

Middle.—Facies characterized by abundance of Lagenidae (especially *Lenticulina* and *Dentalina*), Rotaliidae (*Gyroidina* and *Valvulineria*), and Anomalinidae (*Anomalina*). Characteristic of upper and lower marl units.

Lower.—Facies characterized by abundance of Buliminidae (*Bulimina, Virgulina*, and *Neobulimina*). Characteristic of lower clay unit.

Sketches diagrammatic; after illustrations by Tappan (1940).

deposited in shallower water than were the older units of the Grayson.[2] The predominance

[2] Dr. Fred B Phleger (personal communication) notes that the association of abundant lituolids and globigerinids in the upper clay is anomalous as compared with associations in the modern ocean. The numbers of *Globigerina* in samples from this unit would in Phleger's opinion indicate water depths of 100 fathoms or more. He reasons from this that either the ecologic adjustments of the

of Buliminidae in the lower clay suggests that this unit was deposited in deeper water than either of the marl units above or below it.

Historical Synthesis

The inference, based on Foraminifera, that the seas tended to become shallower toward the close of Grayson time is thus in harmony with the trend toward emergence as independently inferred from the megafossils, lithologic characteristics, and structure. However, the foraminiferal populations suggest that this trend toward emergence was not uniform.

After the shelly limestone of the Main Street had been deposited, increasing amounts of clay began to settle in this area, mixing with the calcareous tests of micro-organisms and other fine organic débris to form the marly beds of the lower Grayson. Shellfish living on these bottoms began to diminish in numbers as the sediment became more clayey; perhaps the influx of sediment had become too rapid to favor the survival of slowly maturing sessile or sluggishly vagrant benthonic animals. Perhaps also the increase in clay was a reflection of deepening waters which placed these bottoms out of reach of any but the finest sediment carried in by rivers or churned up by waves along a submerging shore. At least this is suggested by the fact that as the lower clay began to be formed the complexion of the benthonic foraminiferal population changed to one dominated by the buliminids, indicating that the waters over the bottom had probably deepened.

The disconformity at the base of the upper marl shows that some part of the sedimentary record has been lost by submarine erosion. It may be inferred therefore that, following the deposition of that part of the lower clay which has been preserved, the seas became shallower, so that some of the sediment previously deposited was swept away again by currents. With renewed rising of the sea, there slowly accumulated above this scoured bottom a highly fossiliferous concentrate that contained in places more than 100,000 foraminiferal tests per cubic centimeter. Many fluctuations in depth of water and character of bottom are probably recorded in the alternating beds of clay, marl, and marly limestone of the upper marly unit. On the whole, however, the addition of sediment was not so rapid as to prevent the growth of a prolific and varied benthonic assemblage of clams, echinoids, and gastropods. In time the waters became shallower, and a diversified assemblage of calcareous benthonic Foraminifera gave way to one dominated by the agglutinated tests of the Lituolidae. The coquinitic Buda limestone with its innumerable broken shells may well record the roughness of the surf, along a strand that moved back and forth across this region before the floor of the sea became a part of the land at the close of Comanchean time.

globigerinids have changed with the evolution of the group, or else that the associations in the upper clay are artificial. While there is nothing in the condition of the specimens to suggest the latter alternative, more evidence than is now at hand would certainly be necessary to establish the former.

References Cited

Bailey, T. L., Evans, F. G., and Adkins, W. S., 1945, Revision of stratigraphy of part of Cretaceous in Tyler Basin, northeast Texas: Am. Assoc. Petroleum Geologists Bull., v. 29, p. 170–186.

Cobban, W. A., and Reeside, J. B., Jr., 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geol. Soc. America Bull, v. 63, p. 1011–1044.

Cushman, J. A., 1948, Foraminifera, their classification and economic use: Cambridge, Mass., Harvard Press, 605 p.

Dodge, C. F., 1952, Stratigraphy of the Woodbine formation in the Arlington area, Tarrant County, Texas: Field and Lab., v. 20, p. 66–78.

Glaessner, M. F., 1948, Principles of Micropaleontology, New York, John Wiley, 296 p.

Hussey, K. M., and Campbell, C. B., 1951, A new method of sample preparation: Jour. Paleontology, v. 25, p. 224–226.

Lowman, S. W., 1949, Sedimentary facies in Gulf Coast: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 1939–1997.

Phleger, F. B, 1951, Ecology of Foraminifera, northwest Gulf of Mexico, Pt. 1. Foraminifera distribution: Geol. Soc. America Mem. 46, p. 1–88.

Scott, Gayle, 1940, Paleoecological factors controlling distribution of Cretaceous ammonoids in Texas area: Am. Assoc. Petroleum Geologists Bull., v. 24, p. 1164–1203.

Tappan, Helen, 1940, Foraminifera from the Grayson formation of northern Texas: Jour. Paleontology, v. 14, p. 93–126.

Department of Geology, Southern Methodist University, Dallas, Texas

Manuscript Received by the Secretary of the Society, April 6, 1953

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 337-348, 6 FIGS. APRIL 1954

LOW-VELOCITY LAYERS IN THE EARTH'S MANTLE

BY B. GUTENBERG

ABSTRACT

There are indications of two low-velocity layers in the earth's crust and mantle, one, in the continents, at depths between roughly 10 and 20 km, the other at depths from roughly 60 km to about 150 km for *P* and about 250 km for *S*. The first is called here the lithosphere channel, the second the asthenosphere channel. If an earthquake originates in a low-velocity layer, waves leaving the source downward cannot enter the layers with relatively high velocity above the channel and reach the surface unless they reach a layer below the source with a wave velocity at least equal to the maximum velocity above the source. If an earthquake occurs in the lithosphere channel, waves starting downward must consequently reach at least the depth where the velocity equals the maximum reached above the channel (which is about 6¾ km/sec in Southern California) in order to arrive at the surface and to be recorded. The travel-time curve of such waves with a deepest point above the Mohorovičić discontinuity[1] may easily be misinterpreted as caused by waves refracted at a (nonexisting) discontinuity below the source where the velocity is believed to increase suddenly to about 7 km/sec.

A large fraction of the energy in earthquakes originating in a low-velocity layer remains in the channel. In earthquakes with a source above the lithosphere channel, much more energy is transmitted to the epicentral area than in those originating in this channel, and relatively great damage may result.

New evidence for the asthenosphere channel is discussed. It is based mainly on travel times and amplitudes of longitudinal and transverse waves on records of the largest Kern County, California, earthquakes in July, 1952, for which epicenters are established within about 4 km, and origin times within about a quarter of a second.

CONTENTS

TEXT

	Page
Introduction	337
Lithosphere channel	338
Asthenosphere channel	339
Conclusions	346
References cited	346

ILLUSTRATIONS

Figure	Page
1.—Wave paths of longitudinal waves in the lithosphere channel	338
2.—Observed travel times of *P*	340
3.—Examples of seismograms (beginning) of main earthquake, 1952, July 21	342
4.—Wave paths of longitudinal waves in the asthenosphere channel	343
5.—Observed travel times of *S*	344
6.—Examples of seismograms including *P* and *S* phases of largest aftershock	345

TABLE

Table	Page
1.—Velocity *V* of *P*, *v* of *S*, and Poisson's ratio as function of depth	345

INTRODUCTION

The investigation of low-velocity layers in the earth presents relatively great difficulties, mainly because no rays reaching the surface can have their deepest points in such layers, if the decrease of velocity with depth is greater

[1] The Mohorovičić discontinuity is the upper boundary of the (ultrabasic) material in which the velocity of longitudinal waves is between about 8 and 8¼ km/sec. It is at a depth of about 10 km below sea level under deep ocean basins, 30± km deep under most continental lowlands, and may be as deep as 50± km under high mountains.

than the critical value given by $dv/dr = v/r$ which in the earth's crust is about 0.13 km/sec per 100 km for longitudinal and about 0.07 km/sec per 100 km for transverse waves. On records written by instruments in the resulting shadow zone at the earth's surface, phases caused by diffracted waves or waves along other paths are frequently misinterpreted as produced by direct waves. The rather rapid decrease in amplitudes along the shadow zone is usually the only clear evidence of a low-velocity channel.

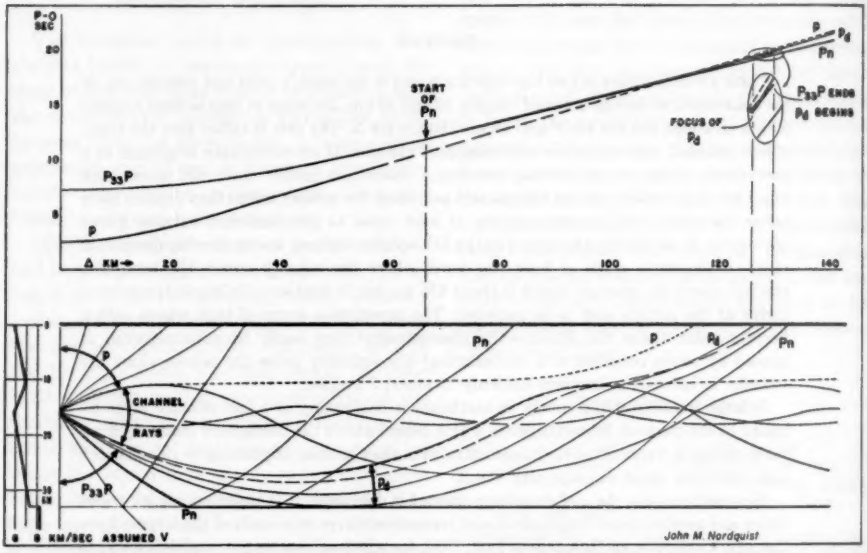

FIGURE 1.—WAVE PATHS OF LONGITUDINAL WAVES IN THE LITHOSPHERE CHANNEL AND CORRESPONDING TRAVEL TIMES
Assumed velocities at lower left

There are now indications for two such channels in the outer portion of the earth, one centering at a depth of about 15 km, the other at a depth of roughly 100 km. Mainly as a matter of convenience we will call the first the "lithosphere channel," the second the "asthenosphere channel."

LITHOSPHERE CHANNEL

The lithosphere channel was originally suggested (Gutenberg, 1951a, p. 429) to remove the discrepancy that in the continents, at a depth of about 10 km, higher wave velocities were found from records produced by artificial explosions at the surface than from earthquake records. In addition, this hypothesis gives the same origin time for longitudinal and transverse waves, whereas previously in most earthquakes the transverse waves (S) seemed to originate either earlier than the longitudinal waves (P) or at a different point. The hypothesis of a low-velocity lithosphere layer also agrees with the rapid decrease in amplitudes of direct longitudinal waves (p) at distances up to 140 km (Gutenberg, 1951b, p. 148). This channel may be identical with the "wave guide formed by a superficial sialic layer" found by Press and Ewing (1952, p. 219, 224). It may be a consequence of phase changes in minerals (Gutenberg, 1951a, p. 431). In laboratory experiments Hughes and Cross (1951) have found indications of a maximum wave velocity in several rock types if temperature and pressure are increased to values to be expected at a depth of roughly 10 km, and possible indications of a decrease in velocity at higher pressures and temperatures; this would correspond to the lithosphere channel.

To get a better idea of the wave paths in-

volved in the channel, Mr. J. M. Nordquist constructed Figure 1 on the assumption that the earthquake focus is at the depth having the minimum velocity. While the author considers the assumed velocities (lower left in Fig. 1) a fair approximation to the actual velocities, significant differences from region to region as well as systematic deviations from the assumed values must be expected. For example, no sudden increase in velocity between the channel and the Mohorovičić discontinuity has been assumed, while actually there is good evidence of waves reflected from a discontinuity several km above the Mohorovičić discontinuity. In some portions of Southern California with a depth of about 32 km for the Mohorovičić discontinuity the second reflecting surface is about 5 km shallower. This has been found by Gutenberg (1951b, p. 158) from earthquake records, and G. G. Shor (unpublished manuscript) has obtained corresponding reflection records of blasts by using multiple-trace prospecting-type seismographs. Similar reflection records from explosions near Blaubeuren (Southern Germany) have been reproduced by Reich (1953, p. 234) who found the shallower discontinuity there at a depth of about 20 km, about 8 km above the Mohorovičić discontinuity.

The main effect of the low-velocity layer is the relatively large percentage of energy which is expected to enter the channel if an earthquake occurs in its central portion. In this case, the rays which limit the channel upward and downward have angles of incidence $+i^*$ and $-i^*$ respectively which are given by

$$\sin i^* = \frac{r_m}{r_s}\frac{v_s}{v_m} \qquad (1)$$

where v_s is the velocity at the source, v_m is the maximum velocity between the source and the earth's surface, r_s and r_m are the corresponding radii. The angle $(180° - 2i^*)$ between the rays limiting the channel increases rapidly as v_s/v_m decreases below r_s/r_m. In addition, under otherwise equal circumstances the total energy flow in the direction of the rays with an angle of incidence i_s at the source is proportional to $\sin i_s$ and consequently has a maximum in the horizontal directions (equator of the sphere around the source). On the assumptions made in Figure 1, about half the energy enters the channel, and only about one fourth flows upward toward the surface of the earth and one fourth downward into the earth's interior. If the source moves upward toward the layer with maximum velocity, an increasing portion of the total energy flows toward the surface. This may explain why in relatively shallow shocks the damage near the epicenter is sometimes unexpectedly great.

Rays leaving a source in the lithosphere channel downward with an angle of incidence smaller than i^*, but greater than the angle i', for which approximately $\sin i' = v_s/8.2$ (8.2 = velocity below the Mohorovičić discontinuity), reach the surface of the earth within a few hundred kilometers from the epicenter. Their travel times usually form a curve (p_d) with a focal point and an apparent velocity close to v_m (Insert, upper right, Fig. 1). Such a travel-time curve is frequently misinterpreted as caused by waves refracted at a (nonexisting) discontinuity below which the velocity is believed to jump to a value near v_m.

Asthenosphere Channel

The asthenosphere channel was found by Gutenberg (1926, p. 29) from the marked decrease in amplitudes of P at distances between a few hundred and about 1700 km where the amplitudes become again relatively large. This was confirmed in a number of later papers from discussion of amplitudes of P and S waves in shallow as well as deep earthquakes (*e.g.*, Gutenberg and Richter, 1939, p. 534; Gutenberg, 1948, p. 125–129, 143). More accurate results on the velocity of P and S waves were based on travel times of deep-focus earthquakes by Gutenberg (1952b; 1953, p. 228).

New evidence for the asthenosphere channel is now available from a study of records of the Kern County earthquakes in 1952. All stations with which the Pasadena station exchanges bulletins were asked for their records of the main earthquake and some of the aftershocks. Records of 130 stations have been received, of which 101 were useful in the study of the travel times of P through the mantle. In addition, reports giving the time of P are available from 39 stations, either direct from the station or

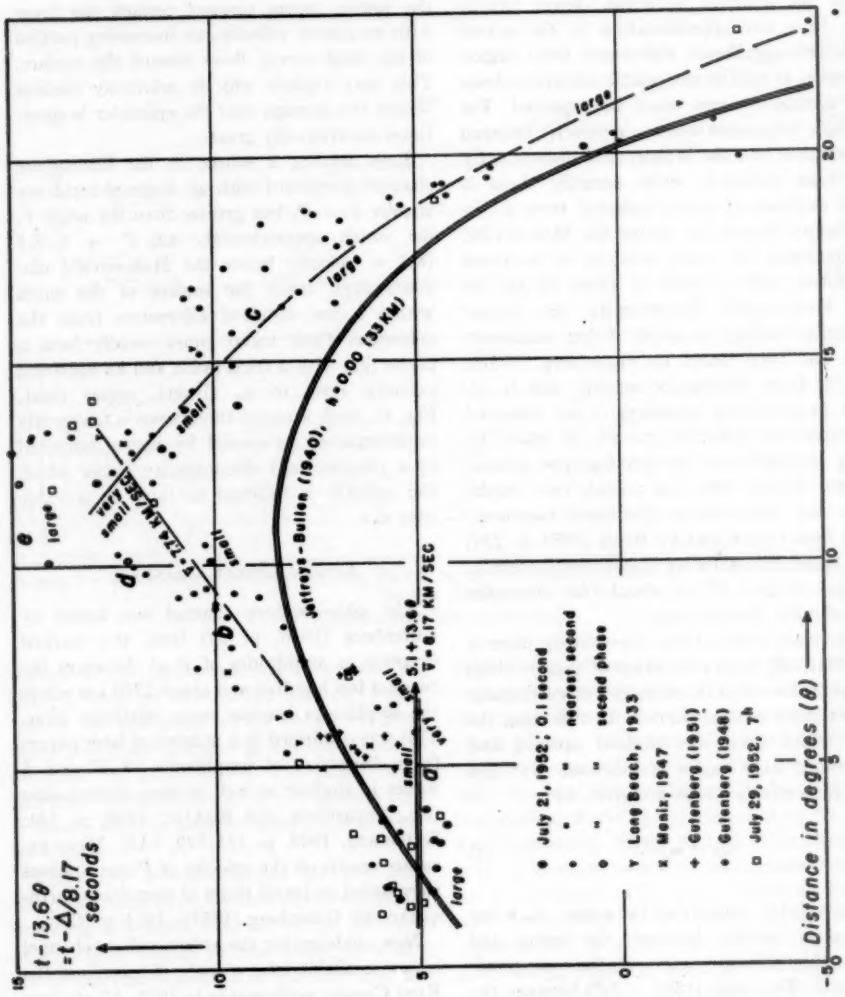

FIGURE 2.—OBSERVED TRAVEL TIMES OF *P* MINUS 13.6 TIMES DISTANCE IN DEGREES

through the U. S. Coast and Geodetic Survey or the International Central Office at Strasbourg. Using records of near-by stations for the main shock (magnitude 7.7) the following co-ordinates of the epicenter were found: Lat. 35°00′ North, Long. 119°02′ West; origin time July 21, 1952 $11^h52^m14.3^s$. For the largest aftershock (magnitude 6.2) on July 29, at $7^h03^m46.6^s$, the resulting co-ordinates, according to Dr. C. F. Richter, were 35°23′ North, 118°51′ West.

In connection with previous investigations by the author of travel times at distances less than 25° (especially Gutenberg, 1948, p. 126) Jeffreys (1952, p. 359) has claimed that "graphical methods are obsolete." This is considered fallacious by the author, and again he has plotted travel times of P for distances less than 25° on a large scale (Fig. 2) before attempting to make a least-square solution. Some travel times observed previously are added in Figure 2. The result justifies the use of graphic methods, since this procedure avoids the combination of different types of phases (Fig. 2) in one least-square solution. Jeffrey's procedure of combining heterogeneous data in least-square solutions and supposing certain mathematical forms without ascertaining first by graphic methods that there is a basis for the assumed form of the travel-time curve may result in conclusions which seem to be well substantiated by small standard errors but actually include greater systematic errors. However, least-square solutions are very useful if the function to be fitted by the observations is known and if there is reason to believe that the systematic errors are negligible.

Previous investigations of travel times of Pn in Southern California at epicentral distances Δ in km between about 1½° and 5° have indicated travel-time curves of the form

$$t = a + b\Delta. \qquad (2)$$

The following values for the constants a and $b = 1/\bar{v}$ in equation (2) have been found ($\bar{v}$ = apparent velocity) for earthquakes in Southern California excluding higher mountain regions:

	a	$\bar{v}$
(a) Manix earthquakes, Richter and Nordquist (1951, p. 352)	5.4	8.2 km/sec
(b) 26 shocks, Gutenberg (1951, p. 151)	5.1	8.1
(c) 26 shocks, 140 km < Δ < 500 km	5.0 ± 0.1	8.07 ± 0.05

Based on the method of least squares applied to 46 data of shocks prior to 1942, (c) is a new solution. A least-square solution of the times of Pn observed at 13 distances between 1.7° and 3.9° in the earthquake of 1952, July 21, 11^h, resulted in

$$a = 5.1 \pm 0.9 \qquad \bar{v} = 8.18 \pm 0.18 \text{ km/sec.}$$

For July 29, 7^h, a was found to be 0.4 ± 0.2 greater. The difference is probably due to the fact that the shock of July 29 occurred closer to the Sierra Nevada at a point where the Mohorovičić discontinuity is slightly deeper. However, a slightly smaller focal depth is not excluded. For blasts in Southern California, Gutenberg (1952a, p. 429) found $a = 8.0$, $\bar{v} = 8.2$ km/sec. From a combination of all these data there can be little doubt that in Southern California the velocity of longitudinal waves immediately below the Mohorovičić discontinuity is between 8.1 and 8.2 km/sec, as in most other regions of the world.

At epicentral distances between 4° and 6° the amplitudes of Pn are very small, and Figure 2 shows that beyond about 6° the actual Pn phase is not recorded. The first recorded waves (near the line b in Fig. 2) are very small (examples of seismograms in Fig. 3) and are probably not propagated following the equations of ray optics but are "diffracted waves." Some larger later phases (d, e) have not yet been investigated in detail.

Beginning at an epicentral distance of about 12°, the first wave in the seismograms follows a travel-time curve with a completely different slope (c in Figs. 2, 3). At distances between 12° and about 15° this phase c is small and may be diffracted. In earlier investigations (Gutenberg, 1948, p. 125) the beginning of strong P waves was found at a distance of about 15°. In the shock of July 21, 1952, P was still small at Alberni (distance 14.9°), but relatively

FIGURE 2.—OBSERVED TRAVEL TIMES OF P MINUS 13.6 TIMES DISTANCE IN DEGREES

large beginning with the record at Lincoln, Nebraska (distance 18.6°). The beginning at Rapid City (distance 15.2° on July 21, 14.9° on July 29, Fig. 6) is intermediate, with a gradual increase in amplitude. Unfortunately, the clock correction there was changing rather rapidly so that the observed arrival times are not accurate enough for our purposes.

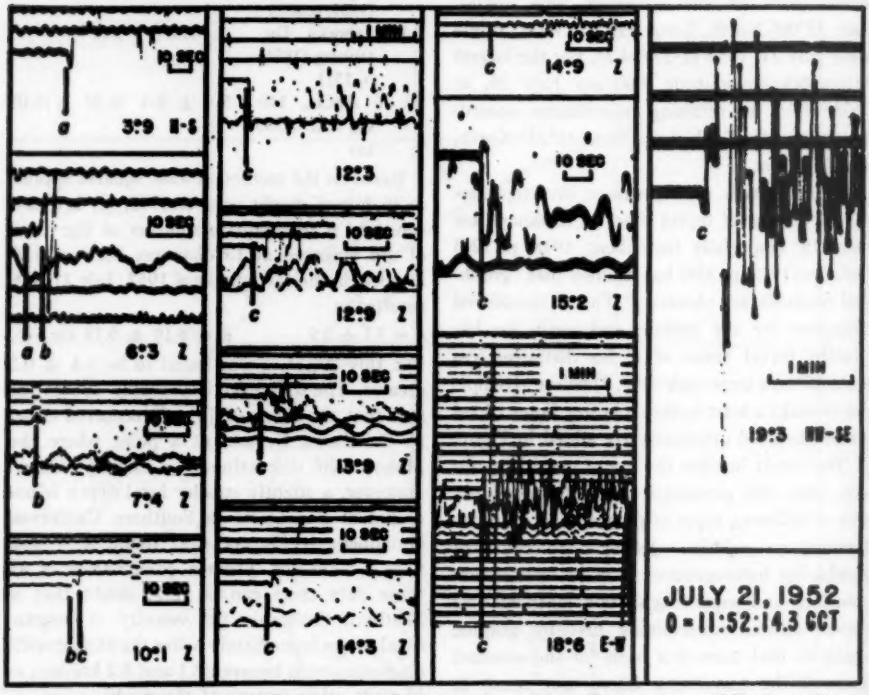

FIGURE 3.—EXAMPLES OF SEISMOGRAMS (BEGINNING) OF MAIN EARTHQUAKE; 1952, JULY 21

Epicentral distances: 3.9° (Berkeley, Galitzin, NS); 6.3° (Shasta, short-period Benioff on film, Vertical); 7.4° (Tucson, short-period Benioff, Vertical); 10.1° (Corvallis, Slichter, Vertical); 12.3° (Bozeman, McComb-Romberg, NS); 12.9° (Seattle, short-period Sprengnether, Vertical); 13.9° (Victoria, short-period Benioff, Vertical); 14.3° (Lubbock, short-period Vertical); 14.9° (Alberni, short-period Willmore-Sharpe, Vertical); 15.2° (Rapid City, Wood-Anderson, EW); 18.6° (Lincoln, McComb-Romberg, EW); 19.3° (Saskatoon, Milne-Shaw, NW-SE).

The travel times and amplitudes indicated in Figure 2 can be explained on the assumption of a low-velocity layer at a depth of roughly 100 km (Gutenberg, 1953, p. 228), the asthenosphere channel. Figure 4, constructed by Mr. Nordquist, shows the geometry of rays passing through this channel. The assumed velocities are probably a good approximation to the actual values in the earth and, contrasting with Figure 1, Figure 4 is probably not only qualitatively but quantitatively representative of the rays. Diffracted waves are not indicated in either figure.

At the depths of the asthenosphere channel the temperature is not far from the melting point, and the effect of increase in temperature with depth, which decreases the wave velocity, is probably not compensated by the opposite effect of the increase in pressure, whereas above and below the channel the pressure effect prevails. Poisson's ratio increases slightly but definitely in the channel and remains greater below it than above (Table 1).

The observations do not exclude the possibility that at a depth of about 10 km below the surface the decrease in velocity due to increasing

temperature becomes greater than the increase by increasing pressure, and that the lithosphere and asthenosphere channels are part of the same phenomenon. The velocities could then decrease

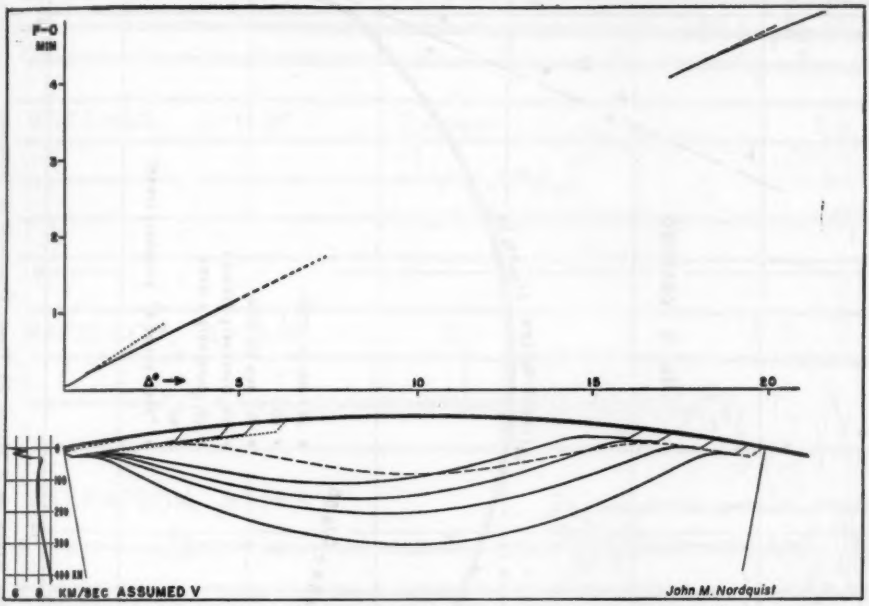

FIGURE 4.—WAVE PATHS OF LONGITUDINAL WAVES IN THE ASTHENOSPHERE CHANNEL AND CORRESPONDING TRAVEL TIMES
Assumed velocities at lower left

in each layer between a depth of about 10 km below the surface and the depth of minimum velocity in the asthenosphere channel.

Investigation of the transverse waves S is much more difficult than that of P. While in a large shock even a small beginning of the seismogram can be detected, if the microseisms are not large and the sensitivity of the instrument is high, a similar small S phase is usually lost in the continuing P group motion. In nearly all seismograms of the July 21 shock the motion recorded during the first minutes was too large by far to discover S at distances less than 25°. However, some seismograms of the much smaller shock of July 29 could be used for the study of S at short distances.

Travel times of Sn in Southern California at distances between about 1½° and 3° were studied recently (a) by Richter and Nordquist (1951, p. 369) in their investigation of the Manix earthquake, and (b) by Gutenberg (1951b, p. 159) for a number of California shocks. They found for the time t at a distance Δ in kilometers or θ in degrees (b from a new solution by use of the method of least squares for 31 data from distances between 150 and 280 km.):

(a) $t = 9.0 + 0.220\Delta = 9.0 + 24.46\theta$
(b) $t = (8.4 \pm 0.3) + (0.222 \pm 0.001)\Delta$
$= 8.4 + 24.69\theta$

The first corresponds to an apparent velocity of about 4.55 km/sec, the second to 4.51 ± 0.02 km/sec. A line corresponding to $8.4 + \Delta/4.55$ has been entered in Figure 5 together with observed travel times of S in the Kern County shocks of July 21 and 29 and in other shocks. Figure 5 is similar to Figure 2 except that there are fewer data and that the branch of S with higher apparent velocity begins at greater epicentral distances (18°±) than the corresponding branch of P. Amplitude observa-

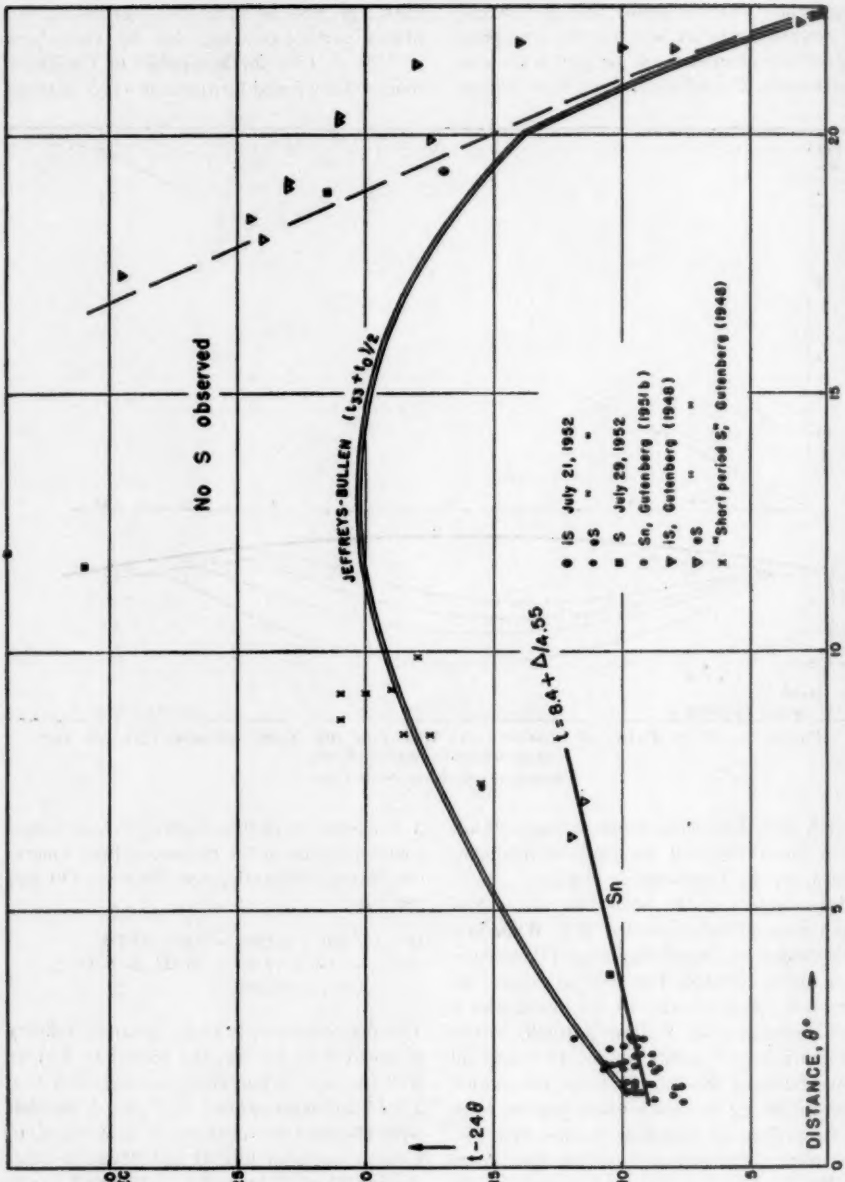

FIGURE 5.—OBSERVED TRAVEL TIMES OF *S* MINUS 24 TIMES DISTANCE IN DEGREES

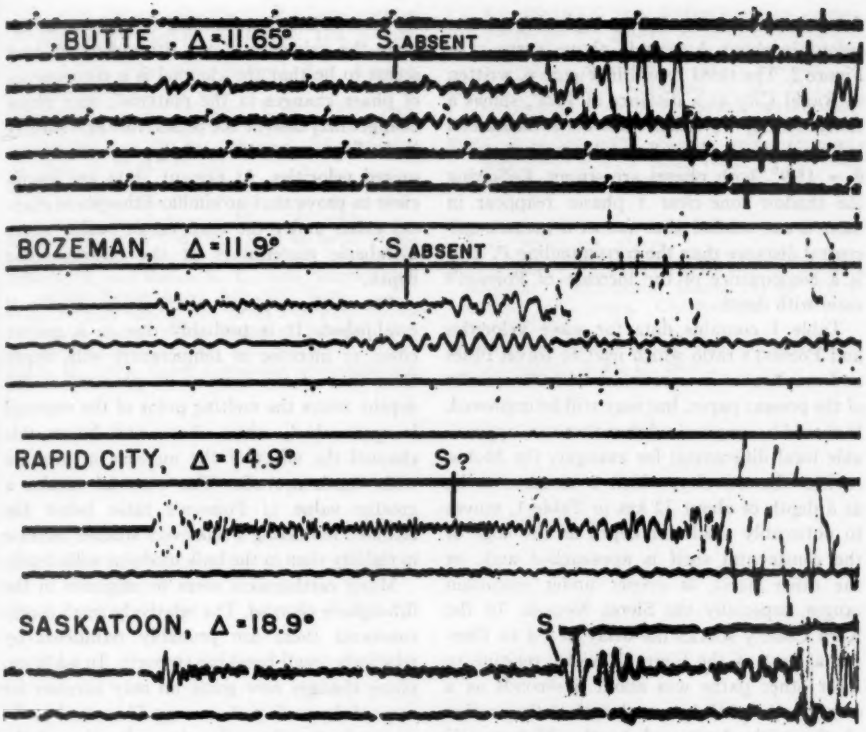

FIGURE 6.—EXAMPLES OF SEISMOGRAMS INCLUDING *P* AND *S* PHASES OF LARGEST AFTERSHOCK, 1952 JULY 29

Epicentral distances: 11.°65 (Butte, Wood-Anderson, NS); 11.°9 (Bozeman, McComb-Romberg); 14.°9 (Rapid City, Wood-Anderson, EW); 18.°9 (Saskatoon, Milne-Shaw, NW-SE).

FIGURE 5.—OBSERVED TRAVEL TIMES OF *S* MINUS 24 TIMES DISTANCE IN DEGREES

TABLE 1.—VELOCITY *V* OF *P*, *v* OF *S*, AND POISSON'S RATIO δ AS FUNCTION OF DEPTH *h* IN SOUTHERN CALIFORNIA

h km	*V* km/sec	*v* km/sec	δ	*h* km	*V* km/sec	*v* km/sec	δ
1	5.9	3.2?		100	7.8	4.4	0.27
5	6.5	3.6?	average	150	7.9	4.3	0.28
10	6¾	4±?	0.25±	200	8.1	4.4	0.28
15	6±?	3¼?		300	8.5	4.6	0.29
20	6¼±?	?	?	400	9.1	4.9	0.29
30	7±	?	?	500	9.6	5.3	0.29
	Mohorovičić discontinuity			600	10.2	5.6	0.29
40	8.15	4.55	0.27				

tions (Gutenberg, 1948, p. 140) show that the focal point of *S* is at a distance of about 19° in Southern California. The new data confirm this result. In Figure 6 examples of records are reproduced. At 11.6° (Butte) the earliest recorded wave is on the branch *b* of Figure 2; the phase looking like *S* with somewhat longer period is about 11 seconds later than given by the Jeffreys-Bullen travel time for *S* in Figure 5, and at Bozeman, θ = 11.9°, it is still more

delayed; the corresponding beginning of the record is about 2 seconds above curve *c* in Figure 2. The third record in Figure 6, written at Rapid City at a distance of 14.9°, shows a fairly strong *P*, which has been mentioned before, but no clear *S*, while at Saskatoon, $\theta = 18.9°$, both phases are strong. Following the shadow zone clear *S* phases reappear in most areas studied thus far at a greater epicentral distance than the corresponding *P*. This is a consequence of the increase of Poisson's ratio with depth.

Table 1 contains data for wave velocities and Poisson's ratio which lead to travel times and amplitudes in agreement with the results of the present paper, but may still be improved. It should be emphasized that there are appreciable local differences; for example, the Mohorovičić discontinuity, which is assumed to be at a depth of about 32 km in Table 1, moves to noticeably shallower depth as the edge of the continental shelf is approached and, on the other hand, is deeper under mountain ranges, especially the Sierra Nevada. In the Kern County shocks the delay in *Pn* to Tinemaha, east of the Sierra Nevada, relative to most other paths was about 3 seconds as a consequence of the greater length of the portion of the path downward to the Mohorovičić discontinuity; similar delays were found to Haiwee and Reno.

Conclusions

New data confirm the hypothesis that in the outer 600 km of the earth there are two low-velocity layers, one at depths between about 10 and 20 km, the other at depths between about 60 and 150 km for *P* and between about 60 and 250 km for *S*. The first is here tentatively called the "lithosphere channel," the second the "asthenosphere channel." Since the velocity of longitudinal waves above the lithosphere channel is about 6¾ km in Southern California and velocities of 6½ km/sec have been found elsewhere, there is some doubt whether the lithosphere channel is in or below the so-called granitic layer. It seems to the author (and others) that the extent in depth as well as in horizontal dimensions of the "granitic material" has been overestimated. At present the best working hypothesis to explain the existence of the lithosphere channel seems to be that the channel is a consequence of phase changes in the material; such phase changes may also be the reason for the difficulty in finding reasonable rock types with the required velocities. At present, data are insufficient to prove that no similar lithosphere channel exists under the deep ocean basins where ultrabasic material is at the corresponding depth.

The asthenosphere channel is now well established. It is probably due to a greater effect of increase in temperature with depth than that of the increase in pressure at the depths where the melting point of the material is approached, while above and below this channel the effect of the increase in pressure with depth prevails. The material retains a greater value of Poisson's ratio below the channel, indicating a relatively smaller increase in rigidity than in the bulk modulus with depth.

Many earthquakes seem to originate in the lithosphere channel. The relatively small elastic constants there are probably paralleled by relatively small breaking strength. In addition, phase changes now going on may account for some of the earthquake energy. If an earthquake occurs in the channel, a large fraction of the energy, possibly of the order of 50 per cent of the total released energy, may go into the channel. In the epicentral area earthquakes originating above the channel would exhibit much more energy than those with a source in the channel. This would explain the unusually great damage observed in some relatively small shocks occurring at shallower depth than usual.

References Cited

Gutenberg, B., 1926, Untersuchungen zur Frage, bis zu welcher Tiefe die Erde kristallin ist: Zeitschr. f. Geophysik, v. 2, p. 24–29.

—— 1948, On the layer of relatively low wave velocity at a depth of about 80 km.: Seismol. Soc. America Bull., v. 38, p. 121–148.

—— 1951a, Crustal layers of the continents and oceans: Geol. Soc. America Bull., v. 62, p. 427–440.

—— 1951b, Revised travel times in Southern California: Seismol. Soc. America Bull., v. 41, p. 143–163.

—— 1952a, Waves from blasts recorded in Southern California: Am. Geophys. Union Trans., v. 33, p. 427–431.

—— 1952b, Wave velocities in the outer part of the earth's mantle: Nature, v. 170, p. 289.
—— 1953, Wave velocities at depths between 50 and 600 kilometers: Seismol. Soc. America Bull., v. 43, p. 223–232.
Gutenberg, B., and Richter, C. F., 1939, New evidence for a change in physical conditions at depths near 100 km.: Seismol. Soc. America Bull., v. 29, p. 531–537.
Hughes, D. S., and Cross, J. H., 1951, Elastic wave velocities at high pressures and temperatures: Geophysics, v. 16, p. 577–593.
Jeffreys, H., 1952, The times of P up to 30°: Geophys. Supp., v. 6, p. 348–364.
Jeffreys, H., and Bullen, K. E., 1940, Seismological tables: British Assoc. Adv. Sci., 47 p.
Press, F., and Ewing, M., 1952, Two slow surface waves across North America: Seismol. Soc. America Bull., v. 42, p. 219–228.
Reich, H., 1953, Ueber seismische Beobachtungen der PRAKLA von Reflexionen aus grossen Tiefen bei den grossen Steinbruchsprengungen in Blaubeuren am 4. März und am 10. Mai 1952: Geol. Jahrbuch, v. 68, p. 225–240.
Richter, C. F., and Nordquist, J. M., 1951, Instrumental study of the Manix earthquakes: Seismol. Soc. America Bull., v. 41, p. 347–388.
Tuve, M. *et al.*, 1952, Seismic waves from explosions: Carnegie Inst. Wash., Year Book no. 51, p. 67–69.

Seismological Laboratory, 220 N. San Rafael Ave., Pasadena, Calif.

Publications of the Divison of the Geological Sciences, California Institute of Technology, Pasadena, California, Contribution No. 632

Manuscript Received by the Secretary of the Society, April 17, 1953

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, PP. 349-364, 3 FIGS., 2 PLS. APRIL 1954

LATE WISCONSIN MARINE DRIFT AND ASSOCIATED SEDIMENTS OF THE LOWER FRASER VALLEY, BRITISH COLUMBIA, CANADA

BY J. E. ARMSTRONG AND W. L. BROWN

ABSTRACT

During late Wisconsin time an assemblage of fossiliferous till-like stony clays and associated clays, silts sands, and gravels with an aggregate thickness of 500 feet was deposited in the Lower Fraser Valley of British Columbia. The authors believe these sediments were deposited in the sea during and following the wasting and retreat of a major Cordilleran ice sheet, and during subsequent uplift of the land above sea level. The agents of transportation probably were ice, including shelf-, berg-, and sea ice; glacial meltwater; and sea water. The writers believe the till-like stony clays, called glacial till by previous workers, had more than one origin, as follows: (1) The stony clays are in part marine drift; that is, the stones and some of the finer materials were transported by ice, and the remainder of the finer materials, predominantly clay, were transported by meltwater and sea water. Three modifications of this theory depend largely on how the stones were transported. These are (a) shelf-ice theory, (b) berg-ice theory, and (c) sea-ice theory. (2) The stony clays were in part deposited as a result of submarine erosion in the littoral and sublittoral zones from the action of submarine slides or slopewash, sea currents, and turbidity currents on pre-existing sediments, mainly till and till-like mixtures, during uplift following maximum advance of the ice sheet. The authors have termed this the submarine slopewash theory. The marine drift and slopewash theories are combined in a composite theory which also explains the origin of the associated sediments.

CONTENTS

TEXT

	Page
Introduction	349
Acknowledgments	350
Physical features	350
Regional Pleistocene geology	351
Pleistocene geology of the Lower Fraser Valley	352
Fossiliferous stony clays and related deposits	352
Introduction	352
Distribution and thickness	352
Lithology	353
Internal structural relations	354
External structural relations	356
Mode of origin	356
General statement	356
Submarine glacial theory	358
Marine drift theory	358
Submarine slopewash theory	359
Explanation of text figures	361
Conclusion	362
References cited	362

ILLUSTRATIONS

Figure	Page
1.—Index map showing physiographic features of area and direction of main ice movement	350
2.—Diagrammatic cross sections drawn across a composite area in the Lower Fraser Valley illustrating the advance and retreat of the last major Cordilleran ice sheet and deposition of till, marine drift, and marine slopewash	354
3.—Diagrammatic cross section of a slope in the Lower Fraser Valley illustrating relation of till, marine drift, slopewash, and associated sediments	360

Plate	Facing page
1.—Marine drift and associated deposits	352
2.—Marine drift and associated deposits	353

INTRODUCTION

The Lower Fraser Valley area in the southwestern corner of the mainland of British Columbia, Canada, is the lowland area bordering the Fraser River and extending from the Strait of Georgia (Pacific Ocean) about 80 miles east to the Cascade Mountains, and from the Canada-United States Boundary north about 25 miles to the Coast Mountains (Fig. 1).

Since 1949 the authors have been mapping the Lower Fraser Valley area and adjoining mountains for the Geological Survey of Canada. This study, not yet completed, includes both bedrock geology and geology of the overlying unconsolidated sediments.

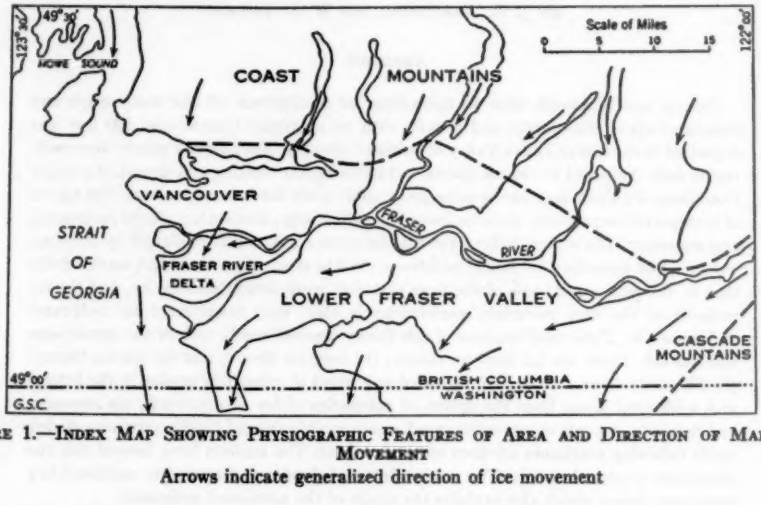

FIGURE 1.—INDEX MAP SHOWING PHYSIOGRAPHIC FEATURES OF AREA AND DIRECTION OF MAIN ICE MOVEMENT

Arrows indicate generalized direction of ice movement

ACKNOWLEDGMENTS

The authors wish to thank all who aided in the field work on which this paper is based, particularly Mr. J. G. Fyles who worked in the field with them part of the 1950 field season and who later conducted his own investigation on similar deposits on the east coast of Vancouver Island, also for the Geological Survey of Canada. Many of the ideas contained in this paper resulted from discussions with Mr. Fyles and other coworkers. Thanks are also extended to Mr. W. M. Draycot and Miss F. J. E. Wagner who collected and identified the fossils. Drs. V. K. Prest, H. S. Bostock, Professors R. P. Goldthwait, J H. Bretz, and Mr. J. G. Fyles read the paper critically, and for this the authors are most grateful.

For aid and encouragement the junior author would especially like to thank Professor J. C. Frye of Kansas University under whose supervision he prepared a master's dissertation containing many of the ideas embodied in this paper.

PHYSICAL FEATURES

The Lower Fraser Valley area is bordered on the north by the Coast Mountains. Only the southwest fringe of these mountains is included in the area under discussion as illustrated in Figure 1, and they have a relief ranging from 5000 to 7000 feet. They rise abruptly in the Lower Fraser Valley area from deep U-shaped valleys, two of which are occupied by the sea, and the remainder by deep lakes and snow-fed rivers. These rivers, which have meandering courses over large sections of their valleys, in places plunge abruptly through steep-walled canyons in a series of rapids and plunge pools.

The Cascade Mountains border the Lower Fraser Valley on the east, but only a low front range about 3000 feet high is in the area under discussion. However, about 15 miles south in the State of Washington the Cascades culminate in Mount Baker 10,750 feet high.

The Lower Fraser Valley area forms part of the Georgia Depression. This depression is mainly submerged, but parts of it rise above the sea as islands in the Strait of Georgia, and as lowlands on the east coast of Vancouver Island and on the mainland of British Columbia. The depression is about 25 miles wide, 100 miles long, and up to 1300 feet deep in the Strait of Georgia (Bostock, 1948, p. 89).

The dominant physiographic feature of the

Lower Fraser Valley area is the Fraser River which occupies an apparently post-Glacial valley up to 3 miles wide and 50 or more feet deep in the much larger lowland area. It terminates in a growing delta 19 miles long and 15 miles wide.

North and south of the valley of the Fraser River and composing most of the Lower Fraser Valley area are wide relatively flat-topped uplands separated by wide flat-bottomed valleys. Most of these uplands consist largely of unconsolidated deposits and do not exceed 500 feet in elevation although three bedrock uplands exceed 1000 feet. Many of these uplands rise abruptly from the intervening valleys by a series of wave-cut and river-cut terraces. The uplands range in size from 1 to 150 square miles and are generally elongated in an east-west direction.

The physiographic features described—namely (1) the Coast and Cascade Mountains, (2) the Lower Fraser Valley lowland, (3) the Fraser River, and (4) the Georgia Depression—had a great influence on the Pleistocene history of the area under discussion, and at various times one or more of these features were controlling factors in either sedimentation or ice movement.

Regional Pleistocene Geology

The Pleistocene geology of the Canadian Cordillera is only sketchily known, and most of the information is of a geomorphological nature concerning scattered local areas. However, a generalized picture of the growth and decay of the Cordilleran ice sheets may be sketched somewhat as follows (Armstrong and Tipper, 1948, p. 308, 309). Assuming that conditions of precipitation during the Pleistocene were similar to those of today, it would follow that in British Columbia much the greatest accumulation of ice was on the Coast Mountains. The major area of accumulation is believed to have been slightly east of the crest of the Coast Mountains in the area opposite Queen Charlotte Sound about 250 miles northwest of the International Boundary. Here the mainland would not be protected by the island fringe from the moisture-laden westerlies. Although this area was the main center of ice accumulation, there were many lesser centers,

Table 1.—Sequence of Events in Pleistocene and Recent Time, Lower Fraser Valley*

9	Alluvial, deltaic, estuarine, and marine sediments deposited in the flood plains, deltas, and channels of the Fraser River and smaller streams in post-Glacial time. Maximum thickness 700 feet.
8	Outwash sands and gravels deposited by valley glaciers. The relation of these glaciers to the Cordilleran ice sheet (5) is not fully established. They may represent the last local advance of the ice sheet or they may represent a later period of glaciation. Maximum thickness 75 feet.
7	*Beach gravels* and *littoral sands* deposited during uplift of land and marine erosion of older sediments. In part younger than the outwash sands and gravels (8). Maximum thickness 25 feet.
6	*Fossiliferous stony clays, marine clays*, minor *silts* and *sands* deposited by ice, meltwater, and sea water during and following retreat of the Cordilleran ice sheet (5) and subsequent uplift. The stony clays include both marine drift and normal marine sediments. Maximum thickness 500 feet.
5	*Glacial tills* and related *stratified drift* deposited by a major Cordilleran ice sheet. At least two advances of ice are indicated, separated by a nonglacial interval† (probably Wisconsin). Maximum thickness 300 feet.
4	Sands, silts, clays, and peats containing plant remains. These sediments were deposited during an interglacial time which had a temperate climate somewhat similar to the present day climate. Maximum thickness 500 feet.
3	Glacial tills, associated varved clays, outwash sands, and gravels, deposited during several local advances and retreats of a major Cordilleran ice sheet (probably pre-Wisconsin). Maximum thickness 500 feet.
2	Older glacial, non- or interglacial, and preglacial sediments as indicated by deep well records. Insufficient evidence to determine actual sequence. Probably Pliocene included here. Maximum thickness 1500 feet.
1	Eocene, Oligocene, and probably Miocene sandstones, shales, and conglomerates.

* Sediments discussed in detail in this paper are in italics.

† Nonglacial deposits refer to sediments found between two tills, but in which no evidence of interglacial climate has been found.

which became overshadowed by ice from the principal area during maximum glaciation. During this time a Cordilleran glacial complex, at least 7500 thick over the valleys, extended from south of the Canada-United States Boundary 1200 miles northwest to the Yukon Territory and Alaska. At least two major glacial stages are recorded by two tills separated by

interglacial deposits in the Pleistocene sediments of most of British Columbia.

Pleistocene Geology of the Lower Fraser Valley

Geological events in Pleistocene and Recent time in the Lower Fraser Valley area are synopsized in Table 1.

Study of Table 1 indicates that the area was subjected to at least two major glaciations (3 and 5), each with more than one local ice advance. Other older major glaciations are suggested but not proven (2). One late period of minor glaciation (8) is also suggested, but it may have been a local phase of (5). Both major episodes of glaciation (3 and 5) reached ice-sheet proportions during their maxima, at which time they were at least 7500 feet thick over the valleys. At this stage glacial flow independent of topography is indicated by th almost uniform strike (N. 10°-25° E.) of striae on the Coast Mountains north of the Lower Fraser Valley area. Only one direction of striae has been observed on the summits. In both major glaciations the ice advanced south of the Canada-United States Boundary at least 150 miles.

Fossiliferous Stony Clays and Related Deposits

Introduction

Following the maximum advance of the last Cordilleran ice sheet (5) across the Lower Fraser Valley the land was at least 750 feet below present altitudes. Possibly the maximum post-ice-sheet submergence was much more, and in the section on Explanation of Text Figures the authors state their reasons for suggesting this. The ice sheet (5) at its greatest development was at least 7500 feet thick. During the maximum advance and probably during the early stages of retreat and local readvances the ice sheet deposited normal tills consisting of hard, compact admixtures of clay, silt, sand, and stones in varying proportions (Pl 1, fig. 1). Substratified drift is found in places in the tills and between tills. The till sheets range in thickness from a fraction of a foot to 100 feet, averaging approximately 20 feet. The tills originally blanketed the uplands; that is, they were deposited on pre-existing hills, modifying their shapes only slightly (Fig. 2, cross section 2).

During and following the later stages of retreat of the Cordilleran ice sheet (5) the region rose above the sea. Probably this emergence was not uniform, and evidence suggests lesser submergences. Concomitant with this land-sea adjustment, fossiliferous stony clays, normal marine clays, and minor silts and sands (6) as well as beach gravels and littoral sands (7) were deposited. Further discussion in this paper is concerned primarily with these deposits.

Distribution and Thickness

The fossiliferous stony clays are best exposed on the uplands of the Lower Fraser Valley area. In much of the area north of the Fraser River, and in the western part of the area south of that river, they occur mainly as a relatively thin mantle up to 25 feet thick overlying till. They appear to grade downward into till in some places (Pl. 1, fig. 2). In other places, particularly on marine terraces, they are separated from till by marine clays, sands, and silts (6) (Pl. 2, fig. 1). In most of this area they occur below a thin mantle of beach gravels and littoral sands. In a few places north of the Fraser River and Burrard Inlet, stony clays occur as foreset or topset beds in raised delta

---

Plate 1.—Marine Drift and Associated Deposits

Figure 1.—Two Tills (5) Overlying Interglacial Sediments (4)
Cleveland Damsite, Capilano River. Elevation about 450 feet.

Figure 2.—Fossiliferous Stony Clay (6) Overlain by Littoral Sands and Beach Gravels (7)
Ocean Park sea cliffs along Strait of Georgia in Surrey Municipality, elevation about 150 feet.

Figure 3.—Coarse Beach Gravels (7) Overlying Stony Clay (6)
West Vancouver. Elevation about 150 feet.

Figure 4.—Fossiliferous Silty Stony Clay
Bear Creek Brickyard. Elevation about 100 feet.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

MARINE DRIFT AND ASSOCIATED DEPOSITS

FIGURE 2

FIGURE 1

FIGURE 3

MARINE DRIFT AND ASSOCIATED DEPOSITS

deposits (Pl. 2, figs. 2, 3). The stony clays thicken eastward in the lower Fraser Valley, and sections up to 450 feet have been observed in the central part of the valley, where the exposed area of stony clays is in excess of 100 square miles. In much of this latter area they appear to lie directly on what are believed to be pre-till (5) gravels and sands (4 and 5).

The fossiliferous stony clays are very poorly exposed in the wide lowland areas between the uplands. However, drill records in these areas indicate their presence beneath and interbedded with normal marine clays, silts, and sands (6). The maximum thickness indicated by drilling is 500 feet. The normal marine clays grade into the fossiliferous stony clays of marine and glacio-marine origin. The normal marine clays are generally best developed and much thicker in areas below 75 feet in elevation, and the stony clays in areas above 75, but many exceptions to this rule are to be found.

The beach gravels (7) are exposed at the surface on most of the uplands in the western part of the Lower Fraser Valley and on a few knobs in the central and eastern parts of the valley. Normally they are 1 to 3 feet thick, but may vary from a few scattered boulders to 12 feet of poorly stratified gravels (Pl. 1, fig. 3).

The larger areas of littoral sands (7) occur mainly on marine terraces or in the valleys in areas downslope from where wave action has breached the till and stony clay and eroded and redeposited the underlying (4) sands. Small areas of sand occur throughout the uplands where till has been subjected to wave washing.

Lithology

The term stony clay has been loosely applied by the authors to a whole range of materials from a very stony sandy silt to a clay containing a few small grit fragments. All these facies appear to grade into one another. However, the most characteristic facies, particularly in the central and eastern parts of the area where the deposits are thick and widespread, is a fossiliferous stony silty clay (Pl. 1, fig. 4). In the western parts of the area, where the deposits are thinner and less continuous, a fossiliferous till-like deposit is characteristic (Pl. 1, fig. 2; Pl. 2, fig. 1). Most previous workers in the area mapped both these types of stony clay as normal tills, although Johnston (1923, p. 50) suggested that some were possibly deposited by shelf ice or floating ice. The stony silty clays consist of about half silt and half clay and contain scattered pebbles, cobbles, and boulders. The stones generally make up less than 5 per cent of the volume, and in places only one or two stones may be observed per cubic yard. Most of the stones are pebble and cobble size, but scattered boulders up to 10 feet in diameter are found. Marine fossils occur throughout. The till-like deposits are a mixture of sand, silt, clay, grit, and stones very similar to the underlying tills. Stones and clay normally do not make up more than 20 per cent of the volume, and sand, silt, and grit make up the remainder. Abundant fossils, lack of compaction, and the interbedded relations with normal marine clays, silts, and sands distinguish these deposits from true till.

Fossiliferous stony silts less than 10 feet thick also occur as foreset and topset beds in raised delta gravel and sand deposits (Pl. 2, figs. 2, 3).

The related normal marine clays are greasy, impalpable, brown to gray clays, interbedded with fine sands and silts.

The beach gravels (7) consist in most places of poorly sorted, substratified to nonstratified mixture of pebbles, cobbles, and boulders in a coarse sand matrix (Pl. 1, fig. 3).

PLATE 2.—MARINE DRIFT AND ASSOCIATED DEPOSITS

FIGURE 1.—TILL (5) OVERLAIN BY FOSSILIFEROUS STONY CLAY (6)
Delta Municipality Gravel Pit. Till separated from stony clay by a few inches of silty sand; elevation about 75 feet.

FIGURE 2.—FOSSILIFEROUS STONY SILT (6) OVERLAIN AND UNDERLAIN BY RAISED DELTA GRAVELS (9)
Seymour Area, North Vancouver. The underlying gravels are possibly outwash, elevation about 200 feet.

FIGURE 3.—FOSSILIFEROUS STONY SILT (6) OVERLAIN AND UNDERLAIN BY RAISED DELTA GRAVELS (9)
Seymour Area, North Vancouver. The underlying gravels are possibly outwash, elevation about 200 feet.

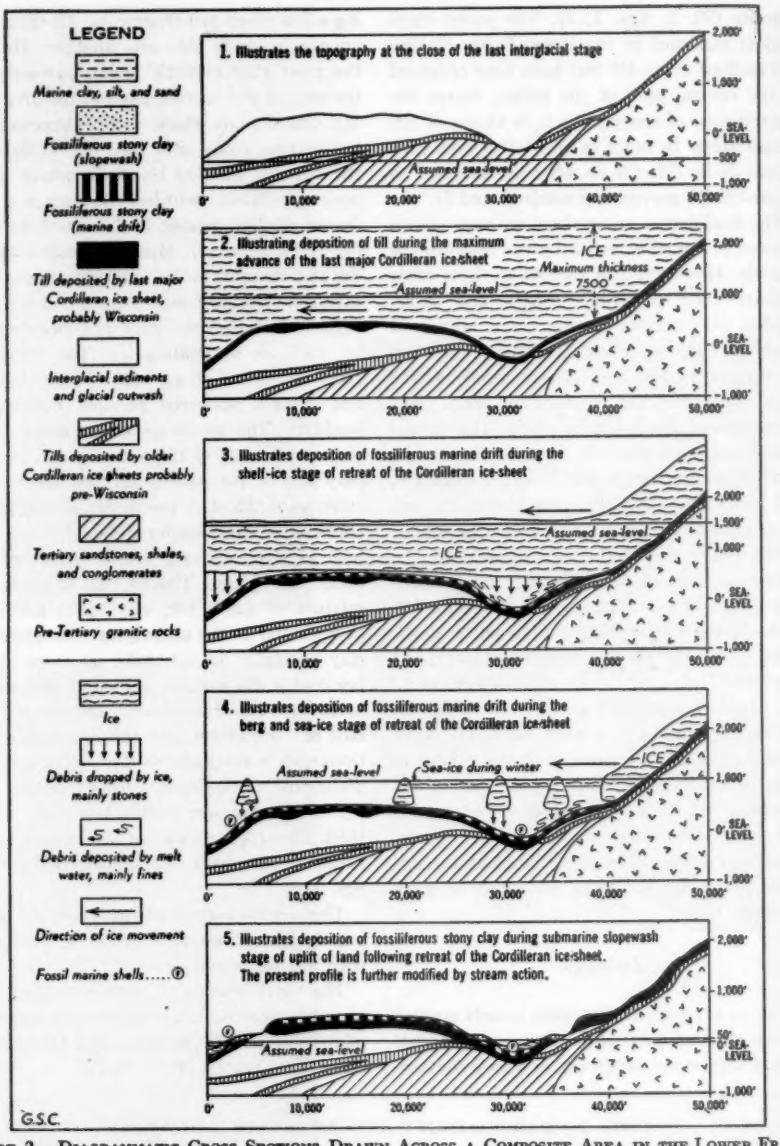
LEGEND
Marine clay, silt, and sand
Fossiliferous stony clay (slopewash)
Fossiliferous stony clay (marine drift)
Till deposited by last major Cordilleran ice sheet, probably Wisconsin
Interglacial sediments and glacial outwash
Tills deposited by older Cordilleran ice sheets probably pre-Wisconsin
Tertiary sandstones, shales, and conglomerates
Pre-Tertiary granitic rocks
Ice
Debris dropped by ice, mainly stones
Debris deposited by melt water, mainly fines
Direction of ice movement
Fossil marine shells.....
1. Illustrates the topography at the close of the last interglacial stage
Assumed sea-level
2. Illustrating deposition of till during the maximum advance of the last major Cordilleran ice-sheet
ICE
Maximum thickness 7500'
Assumed sea-level
3. Illustrates deposition of fossiliferous marine drift during the shelf-ice stage of retreat of the Cordilleran ice-sheet
Assumed sea-level
ICE
4. Illustrates deposition of fossiliferous marine drift during the berg and sea-ice stage of retreat of the Cordilleran ice-sheet
Assumed sea-level
Sea-ice during winter
ICE
5. Illustrates deposition of fossiliferous stony clay during submarine slopewash stage of uplift of land following retreat of the Cordilleran ice-sheet. The present profile is further modified by stream action.
Assumed sea-level
2,000'
1,000'
0' SEA-LEVEL
-500'
-1,000'
0'
10,000'
20,000'
30,000'
40,000'
50,000'
G.S.C.

FIGURE 2.—DIAGRAMMATIC CROSS SECTIONS DRAWN ACROSS A COMPOSITE AREA IN THE LOWER FRASER VALLEY ILLUSTRATING THE ADVANCE AND RETREAT OF THE LAST MAJOR CORDILLERAN ICE SHEET AND DEPOSITION OF TILL, MARINE DRIFT, AND MARINE SLOPEWASH

Internal Structural Relations

The stony clays appear massive and till-like on first inspection, especially the fossiliferous till-like deposits, but close examination normally shows a very indistinct, discontinuous stratification. The interbedded gritty clays exhibit many features of graded bedding and

cyclic deposition. Unfortunately sections showing these features are rare as large exposures are needed. One good section observed in an abandoned clay pit in Surrey Municipality near Sullivan is as follows:

Top of section at elevation 50 feet mean sea level

Feet	
0–⅜	Soil, thin A, nutty to blocky B
⅜–4½	Clay (C horizon) with less than 5% grit and no stones
4½–6½	Clay containing ¼″ discontinuous stringers of fine sand and silt; upper contact gradational in respect to progressive downward increase of silt and sand stringers
6½–9	Clay containing about 15% grit and few stones up to 3″ in diameter; pebbles increase in number downward; upper contact gradational
9–10	Clay with less grit, less than 5% stones
10–19½	Clay with about 20% grit, less than 5% stones
19½–20½	Clay with less than 5% grit and stones
20½–21	Clay with 15% grit containing numerous stones
21–24	Clay, almost pure, containing shell fragments
24–34	Clay, grit, and stones increasing, becoming till-like in appearance toward the bottom

This vertical section shows the gradational relationships between stony gritty clay and clay containing small amounts of grit, and the repetition of these facies.

Another good exposure in a new road cut 1 mile east of the village of Cloverdale shows similar features and bedding relationships. This exposure is 10 feet high and 500 feet long, and is cut into the southeastern slope of a low upland. The western part of the exposure shows stony clay overlying till (5), and the eastern part shows normal marine clay overlapping and interfingering with the stony clay. The midsection of the road cut exhibits several facies of the stony clay—a stony till-like facies, a stony, silty, clay facies, and gritty clay facies. These three facies are repeated throughout the exposure in the following manner. Each sequence grades from stony, till-like clay through silty clay containing a few stones, into clay containing 15 per cent grit and sand and no stones. The gritty clay at the top of each sequence is about 1 foot thick and is bedded with clay beds 1–2 inches thick separated by thin silt partings. When the exposure is damp the gritty clay part of each sequence is readily observable and shows that the sequences are contorted. Asymmetrical to overturned folds are present. in parts of the road cut. However, unlike folds caused by differential pressure, the folding or contortion is confined to one sequence in one place, although all sequences apparently are contorted along the length of the exposure. The folds have steep eastern or downhill limbs and flat to gently inclined western or uphill limbs. The general effect is one of slumping downhill simultaneous with the rhythmic deposition of the stony till-like to gritty clay sequences.

The very thick sections of stony silty clay show interbedded normal marine clay, silt, and sand throughout, although individual beds of stony clay are up to 50 feet thick. In some of the fossiliferous stony clays exposed in the marine terraces of the uplands, the pebbles rest upon a thin layer of very coarse sand surrounded by the gritty, silty, clay matrix typical of some of the stony clays. This feature is apparent on numerous present-day beaches and tidal flats where, if a boulder or cobble partly buried in sand and silt is removed, a gravelly to coarse sand layer may be observed lining the hole left. This layer separates it from the surrounding matrix of sand and silt.

The marine fossils found in the unoxidized portion of the stony clays are remarkably preserved. Whole shells retaining their natural colors and, in places, still covered by the pericardium are not uncommon.

Up to the end of 1953 a total of 42 species of fossil marine shells had been collected and identified from the stony clays and associated normal marine sediments. They were collected from 50 localities ranging from 5 to 575 feet above present sea level. Marine shells similar to these assemblages are now found in the sea in latitudes ranging from 60° to 63° N. or 11° to 14° (760 to 950 miles) north of the Lower Fraser Valley area. Miss F. J. E. Wagner and W. M. Draycot have identified the following fossils:

Pelecypoda
Axinopsida serricatus
Chlamys hericius
Chlamys hindsii

Chlamys cf. *C. jordani*
Clinocardium blandum
Clinocardium ciliatum
Clinocardium comoxense
Clinocardium fucanum
Clinocardium nuttalli
Hiatella arctica
Macoma calcarea
Macoma incongrua
Macoma inconspicua
Mya truncata
Mytilus edulis
Nucula tenuis
Nuculana fossa
Nuculana minuta
Pandora grandis
Propeamusium alaskense
Prototchaca staminea
Saxidomus giganteus
Schizothaerus capax
Serripes groenlandicus
Spisula voyi
Volsella modiolus

Gastropoda
Acamaea digitalis
Buccinum plectrum
Colus jordani
Littorina scutulata
Margarites pupillus
Natica aleutica
Natica claussa
Neptunea lirata
Oenopota pribilova?
Propebela quadra
Trichotropis cancellata
Turbonilla pugetensis

Annelida:
Serpula vermicularis

Cirrepedia
Balanus cf. *B. balanoides*

Echinoidea
Strongylocentrotus cf. *S. drobachiensis*

The related normal marine clays are massive to horizontally bedded, with beds ranging from 2 to 6 inches in thickness.

External Structural Relations

In the area north of the Fraser River and in the western part of the area south of the Fraser River the stony clays and related deposits normally overlie till (Pl. 1, fig. 2; Pl. 2, fig. 1). In many of the upland areas a distinct relation between till, stony clay, and microtopography was observed. Sections up to 25 feet thick, although normally less than 10 feet, exhibit a gradation upward from the top of true till through silty and gritty bedded clay into a fossiliferous stony till-like deposit. This sequence is generally found between low rounded hillocks of till. Laterally the stony clays lap upon the till hillocks and become less stony and more clayey with increasing distance from the hillocks.

The sea-cliff exposures along the Strait of Georgia in many places reveal stony clays directly overlying true tills. Here many of the stony clays are very similar in degree of sorting and particle size to the underlying tills. Small lenses of silt and sand are characteristic of the stony clays but not of the tills; however, this feature is not considered a particularly distinguishing one. Rather, the separation is made on the much poorer compaction of the stony clays and the abundance of well-preserved marine fossils throughout them. Numerous fossils indicate that the deposition occurred in the neritic zone. In these exposures the stony clays grade upward into littoral sands and beach gravels (Pl. 1, fig. 2).

Well records and deep cuts in the central and eastern parts of the Lower Fraser Valley indicate that the widespread thick stony, silty clays do not, in most places, lie on tills but on what are believed to be pre-till (5) sands and gravels. Some of the till-like stony clays in the western part of the valley also lie directly on pre-till sands and gravels, especially on the borders of the uplands where the till has been eroded away by wave action prior to the deposition of stony clays. However, this interpretation does not appear to explain why true till is missing beneath the very large areas of stony clays farther east in the valley. To this question the writers have not yet found an answer. Also in this area are large deposits, up to 10 or more square miles in area and 75 feet thick, of well-sorted, outwash sands and gravels (8) overlying the stony silty clays.

Mode of Origin

General statement.—Some of the features of the stony clays that must be explained are as follows:

(1) The stony clays grade from a very sandy stony silt to a clay containing scattered grains of coarse angular sand (our gritty clay). The two most widespread facies are a fossiliferous stony silty clay and a fossiliferous till-like deposit.

(2) In most of the stony clays the stones form part of the mixture and are surrounded by the clayey matrix, but in many of the till-like deposits on raised marine terraces the stones are separated from the clayey matrix by a thin layer of sand.

(3) Most of the stones are glacially faceted and striated.

(4) In many places the fossiliferous till-like stony clays lie directly on true till and on cursory examination appear to grade into till. However, closer examination usually indicates that the stony clays contain more clay than the underlying till, and also that the till is much more compact.

(5) In other places the till-like stony clays are separated from the underlying till by sands, silts, or clays.

(6) The thick, silty, stony clays normally overlie pre-till gravels and sands, not till.

(7) Stony facies are, in many places, interbedded with poorly stratified gritty facies.

(8) In places the stony facies, gritty facies, and underlying till exhibit an intimate areal relation. Many small hillocks of till are circled downslope by stony clay which grades outwardly into gritty clay.

(9) The stony clays in places exhibit rhythmic and graded bedding.

(10) Where the stratification is best developed contorted bedding, apparently due to downhill slumping, may be seen.

(11) Some of the stony and gritty facies are conformable with and interfinger with the normal marine clays at the toes of the upland areas.

(12) All facies of stony clay contain marine fossils.

(13) These fossils are neritic and littoral assemblages.

(14) Most of the neritic fossil assemblages are remarkably well preserved. Many of the barnacles are still attached to stones in their living positions. All these features suggest quiet water conditions.

(15) In contrast many of the littoral fossil assemblages consist largely of broken shells.

(16) The fossils are similar to those now found between latitude 60° and 63° N., or 11° to 14° of latitude north of the Fraser River Valley.

(17) The stony clays are thicker and contain more clay in the eastern than in the western parts of the area.

(18) The stony clays are overlain by littoral sands and beach gravels which appear to be areally related to them.

(19) Record of an erosion interval is probably present in some exposures between the stony clays and underlying till. This interval is represented by complete erosion of the till in a few places so that stony clays lie directly on pre-till sands and gravels. In other places possibly till never was deposited.

(20) Evidence indicates that, immediately prior to deposition of the stony clays, the sea level stood at least 750 feet and possibly much more above present sea level.

The above summary indicates that the origin of the materials constituting the stony clays cannot be ascribed to one simple process. They were apparently deposited in the sea during and following the wasting and retreat of a major Cordilleran ice sheet and during the following uplift of the land above sea level. The agents of transportation probably were ice, including shelf ice, berg ice, and sea ice, glacial meltwater, and sea water. The origin of the till-like facies and other facies containing large stones is the most difficult to explain. If a reasonable explanation can be offered for the origin of these stony clays no difficulty should be encountered in explaining the related gritty clays and normal marine clays. Therefore, the possible origin or origins of the stony clays is considered first. Whatever theory is advanced must account for the stones and fossils in the clays. These could possibly be explained by one of the following theories:

(1) The stony clays were deposited by ice scouring the sea floor and incorporating the fossiliferous sea-floor sediment into a basal moraine; this may be called the submarine glacial theory.

(2) The stony clays are "marine drift" and are compound in origin; that is, most of the materials were transported by ice and meltwater, and the fines worked over and deposited by sea water. Marine life existed in the sea at the time of deposition. Three modifications of this theory may be suggested, depending largely on how the stones were transported: (a) the

shelf-ice glacial theory in which case the glacial ice would extend as a floating mass into the sea; (b) the berg-ice glacial theory in which case the glacial ice would break into bergs which would float into the sea; and (c) the sea-ice theory which would attribute the stony clays to an environment of deposition that would be the marine equivalent of that supposedly surrounding the deposition of varved clays.

(3) The stony clays were deposited as a result of marine erosion in littoral and sublittoral zones and are the result of submarine slides or slopewash, sea currents, and turbidity currents on pre-existing sediments during the uplift of the land which followed the maximum advanced stage of the last Cordilleran ice sheet (5). This may be called the submarine slopewash theory. The writers believe that more than one of the above theories apply to the origin of the stony clays and in the following discussion attempt to show to what extent each theory is applicable.

Submarine glacial theory.—In the descriptions of the fossiliferous tills in the British Isles it is assumed that the fossils were incorporated in the till by scouring of the sea floor by glacial ice. In all cases the fossils are described as much broken and generally concentrated near the base of the till. Obviously the stony clays showing many features of normal sedimentation could not have formed in this manner, but possibly some of the till-like stony clays were formed thus must be considered. Johnston (1923, p. 42) attributes some of the "shelly till" exposed in the Lower Fraser Valley area to "an old sea floor that was ploughed up by the ice." In general the following facts appear to vitiate this theory: (1) most of the fossils in the stony clays are unbroken, (2) barnacles are still attached to the stones upon which they lived, (3) fossils are distributed from top to bottom of the stony clays, (4) some *Chalmys* shells have the valves still attached, (5) the fossiliferous stony clays in many places overlie unfossiliferous till, and (6) in other places the stony clays overlie unfossiliferous sands and gravels. The last two points suggest that no fossiliferous sea-floor sediments existed beneath the deposits of stony clays, prior to the supposed advance of a glacier.

Marine drift theory (Fig. 2).—There are several modifications of this theory, but all are built on the same general hypothesis—*viz.*, the pebbles and cobbles and most of the subpebbles sizes are ice-transported and are dropped into the sea in which marine forms are living, and some of the subpebble-sized sediments are transported by meltwater. Deposition of this latter sediment in the sea is believed to have been contemporaneous with the ice-transported debris.

The first modification of the marine-drift theory called the shelf-ice glacial theory, was suggested by Johnston (1923, p. 50) as one possible explanation for shelly till. This theory envisions the following sequence of events during the wasting of the Cordilleran ice sheet. As the ice sheet thinned it gradually lost contact with the sea floor upon which it had rested and became a floating shelf-type ice similar in general to the Ross Barrier Ice fringing the Antarctic Continent (Roots, 1952, p. 17). Marine life invaded the sea beneath this ice in much the same way as it now exists in water of the fiords of Greenland. The basal parts of the shelf ice would contain large quantities of till-like debris which, while melting proceeded, would be dropped on the sea floor. The sediment so deposited would be similar to the till deposited by the ice sheet when thick enough to move across the sea floor, except that it would not be so compact. In this way the observed sequence of deposits would be derived —*viz.*, till would be directly overlain by fossiliferous marine drift such as in the exposure on the sea cliffs in the western part of the area along the Strait of Georgia (Pl. 1, fig. 2). Also the fossils would be distributed throughout the sediment thus, according with observations. It would also allow the high degree of preservation of the fossils because they would have immediate burial in a material of low permeability.

The Russian literature contains a brief description of what may be similar deposits. Koolik (*in* Archangelsky, 1935, p. 195, 216) postulates that they are the result of ice bergs and ice fields, similar to those today in the Arctic Ocean and Bering Sea, dumping till-like sediments into the sea, around and upon the boreal fauna that lived on the sea bottom. Koolik calls these deposits "marine moraines".

The second modification of the marine drift

theory the writers call the berg-ice glacial theory. In this theory it is assumed that the ice sheet had retreated into the eastern part of the Lower Fraser Valley area and into the great glaciated valleys in the Coast Mountains. This ice would calve into bergs whenever and wherever it reached the sea. The bergs would carry debris away from the shore and drop it onto the sea floor where clay was being deposited by meltwater and where marine life existed. Most of the facts offered in support of the shelf-ice glacial theory would also substantiate this berg-ice glacial theory. The main fact against this theory seems to be the relatively regular distribution of the pebbles and cobbles in most of the stony clays. The authors do not believe that, if bergs were entirely responsible for transportation of the stones, they would be as evenly distributed as by shelf ice. Rather, they probably would occur predominantly in clusters. A few exposures were observed in which this feature was exhibited, suggesting that bergs were responsible for some of the pebbles and cobbles in the stony clays.

On Middleton Island, Alaska, Miller (1953, p. 33) describes deposits lithologically similar to the stony clays but probably older. He refers to them as "conglomeratic" sandy mudstones and believes they were deposited during periods when debris-laden ice from a near-by landmass floated over the site of deposition. The floating ice may have been in the form of continuous shelf, of discrete bergs, or of both shelf and bergs.

The third modification of the marine drift theory may be called the sea-ice theory. This theory postulates conditions analogous to those causing the deposition of varved clays, except of course that the water body receiving the sediments would be the sea and not a fresh-water lake. This would give a sediment similar to varved clays in overall composition but presumably without the varved graded bedding, as salt water is believed to prevent separation of fine sediment into summer and winter fractions. Thus it is assumed that the ice sheet (5) had left the Lower Fraser Valley area and that climatic conditions allowed the formation of extensive sea ice in its place. The conditions would probably be somewhat analogous to those found off the Coast of Baffin Island today (R. P. Goldthwait, 1952, personal communication). Here the Spring freshets in the streams commence before the sea ice breaks up. As a result the streams carry large quantities of both fine and coarse alluvium onto the sea ice which is carried away when the ice breaks up and is dropped on the sea bottom. Landslides off steep hillsides could also account for some of the debris carried by sea ice. The authors believe stony clay deposits formed by the sea-ice theory are much less important than those formed by shelf and berg ice. If the sea-ice theory be accepted to explain most of the stony clays, then sea ice must have been extensively developed in the Georgia Basin for a long period of time. Climatic conditions necessary for such large amounts of sea ice would probably result in the formation of extensive glaciers on the land and so would become a shelf-type ice. Sea ice was probably locally developed in the heads of bays or fiords near river mouths some time during the formation of the stony clays. Sir Archibald Geikie (1863, p. 129–148) in his classic report on the glacial drift of Scotland suggested the berg-ice and sea-ice theories for origin of fossiliferous, stony clays, interbedded with stoneless clays. He grouped these two types of clay under the general term "marine drift".

Much of the stony clay can be considered marine drift formed according to the shelf-ice, berg-ice, and sea-ice modifications of the marine-drift theory. However, the writers believe that some was formed by normal submarine sedimentary processes.

Submarine slopewash theory (Figs. 2, 3).—This theory attempts to explain the origin of stony till-like clays that occur as follows: (1) showing an areal relation of the stony and gritty facies to till hillocks of the local upland topography, (2) forming terraced uplands, (3) showing cyclic deposition and graded bedding, (4) separated from underlying till by gritty clay facies and sand, (5) lying on pre-till sediments from which till was eroded, and (6) forming foreset and topset beds in raised marine deltas (Pl. 2, figs. 2, 3).

Prior to the deposition of these stony clays the major features of the upland and valley topography were the same as today. The uplands were covered by till which in places lay beneath deposits of marine drift. The maximum relief of the area was possibly 150 feet greater

than at present because the stony clays derived according to this theory are estimated to be about 150 feet thick. The uplands had a general morainal topography with rounded rather than to till knobs would fit this explanation. During storms the amounts of unsorted sediment derived from till and marine drift would be large, and the stony till-like facies would ex-

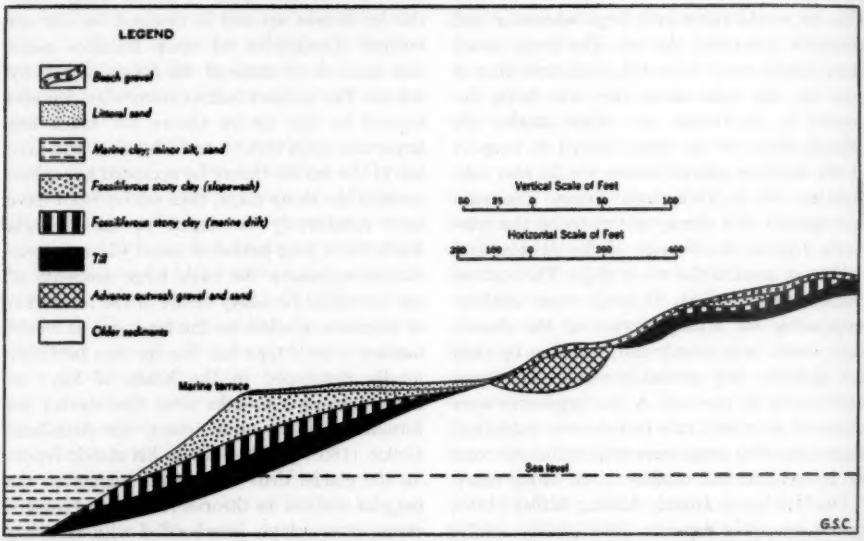

FIGURE 3.—DIAGRAMMATIC CROSS SECTION OF A SLOPE IN THE LOWER FRASER VALLEY ILLUSTRATING RELATION OF TILL, MARINE DRIFT, SLOPEWASH, AND ASSOCIATED SEDIMENTS
This diagram is an enlargement of a slope illustrated in Figure 2, cross section 5

terraced slopes (Fig. 2, cross section 4). At the beginning of deposition the area was just emerging from the sea after the retreat of the ice sheet (5).

The land surface as it rose was progressively eroded by wave action, the high areas eroded directly by waves and the low areas affected concomitantly by the current and deep oscillatory wave motions. This combination produced sediment from the wave erosion of the marine drift and till and provided transportation. The fine fraction would move to the deep waters occupying the wide lowland valleys where normal marine clay would be deposited; unsorted till-like stony clay facies would be deposited a short distance from the areas of erosion after transportation by undertow and longshore currents; and the gritty clay facies would be deposited on the slopes between the sites of stony till-like clay deposition and normal marine clay deposition. The areal relationships exhibited by the various facies of stony clays tend farther from the eroded areas than during normal periods. This would explain the cyclic sedimentation exhibited in places. The movement of this sediment would also be facilitated during storm periods by the increase of submarine currents. Those sediments deposited on slopes would slump during unstable conditions. In this manner the contorted bedding which indicates downhill movement could be explained. This movement would initiate turbidity currents which would produce the graded bedding observed in some exposures.

As this combination of marine erosion, transportation, and deposition was shifted downward across the upland topography the sites of earlier deposition would become sites of erosion. Terraces were formed during this sequence of events when the rate of wave erosion and deposition exceeded rate of uplift.

These terraces, which are rarely more than half a mile wide, were covered by stony clay containing littoral shells. The poorly sorted

mixture of these terrace deposits is believed to have been deposited by the same agents operative today within the littoral zone, although some sorting exists in the form of small discontinuous lenses of sand, silt, or clay. The source of this sediment was till and/or marine drift. If such a deposit is rapidly eroded and the agents of transportation are overloaded, there is little sorting. Observations on modern beaches suggest that sorting takes place when the terrace, initially caused by erosion in the wave zone, becomes so large that the undertow currents transport the sediments over a tidal flat of low gradient. Large boulders are presently moved out onto the tidal flats during storms where till cliffs are undergoing erosion. During a storm a 7-ton block of concrete was moved from a dike in the western part of the area onto the tidal flat. The turbulent currents which subsequently developed around the block increased erosion so as to undermine and eventually bury it in sand and silt. In this manner those boulders incased in sand, as described earlier, may have been emplaced in the terrace deposits.

Explanation of Text Figures

In Figure 2 the writers illustrate by diagrammatic cross sections drawn across a composite area the formation of stony clays during and following the retreat and wasting of the last major Cordilleran ice sheet (5).

Cross section 1 illustrates the topography following the close of the last Interglacial interval (4) and prior to the maximum advance of Cordilleran ice sheet (5); the profile consists of some advance outwash deposits of the last ice sheet (5) and Interglacial (4) and older formations. It is difficult to define the close of the Interglacial interval (4) as the sediments known to be Interglacial are overlain by thick deposits of sands and gravels that could be normal Fraser River floodplain deposits or outwash river deposits many miles from the source ice. It is also difficult to derive a probable figure for the elevation of the land prior to the maximum advance of the last ice sheet. On cross section 1 the assumed sea level is shown as 500 lower than the present sea level. This is an arbitrary figure based on the following information: Interglacial peat in cuts at present-day sea level suggests that the land-sea relationship at that time was similar to that now found; witness the large peat bogs near sea level in the present delta of the Fraser River. However, Interglacial sediments typical of floodplain deposits have been found in deep wells down to 500 feet below sea level, and the assumption has been made that they represent the same Interglacial interval. Therefore an arbitrary sea level of minus 500 has been placed on cross section 1 with the knowledge that it probably records a time prior to any ice advance and with the realization that possibly the land-sea relations then could have been much as they are now; however, the emphasis has been placed on the maximum probable uplift of the land above the sea in the Interglacial (4) interval.

Cross section 2 illustrates the deposition of normal till during the maximum advance of the last major Cordilleran ice sheet (5). The main purpose of this cross section is to show how slightly modified is the underlying topography. Obviously the ice did not bevel off the hills and fill in lowlands with debris. Mainly it plastered till on the pre-ice topography. Although not shown on this cross section the valleys were deepened in places, especially where the ice moved along them. This was especially true in bedrock valleys. The writers have not tried to show in cross section 2 the modifying effects of deposition of advance outwash on the pre-existing topography. As previously stated, it is difficult to separate advance outwash from pre-till floodplain deposits, and as both are poorly exposed no attempt was made to show the modified topography on cross section 2; however, Figure 3 shows the probable relation of advance outwash deposits.

During the maximum advance of the last ice sheet the land was submerged at least 750 feet below the present sea level. Marine terraces and beach gravels are found up to this elevation. Fossil marine shells, including free-swimming forms that lived in 10 to 40 fathoms of water, are found up to 575 feet above present sea level. Deltaic sands and gravels that could be, at least in part, marine occur up to elevations of 1200 feet.

Cross sections 3 and 4 illustrate the deposition of fossiliferous marine drift, mainly stony clays, during the shelf-, berg-, and sea-ice stages of the retreat and wasting of the Cordilleran ice sheet (5). The maximum assumed sea level is indicated at 1500 feet above present sea level in cross section 3. This figure was deduced by reasoning that the greatest depression of the land probably lagged somewhat behind the maximum advance of the ice sheet (5), and that the shelf ice was probably up to 1000 feet thick, a figure arrived at in comparison to Greenland and Antarctic ice. This shelf ice apparently deposited debris in the sea-floor muds, thus forming stony clays that now occur up to elevations of 575 feet above present sea level. During the berg- and sea-ice stages illustrated in cross section 4 the land had probably risen a few hundred feet, and the writers have assumed a sea level of 1000 feet during maximum development of the berg-ice stage. This would allow for bergs up to about 500 feet thick.

All assumed elevations of sea level more than 750 feet above present sea level are rather arbitrarily derived; however, possible overestimates of emergence do not affect the overall picture of the development of the stony clays by the shelf-, berg-, and sea-ice theories. Lack of concrete evidence for sea levels higher than 750 feet could be explained readily by the fact that both shelf ice and berg ice would deposit debris only from their bases and that much of the land above 750 feet elevation was covered by ice as shown in the cross sections.

Cross section 5 of Figure 2 and Figure 3 illustrates a late stage in the deposition of stony clay during the submarine slope-wash stage of uplift of land following retreat of the ice sheet. This stage of deposition undoubtedly overlaps with the shelf-, berg-, and sea-ice stages, especially as there were probably local re-advances of the ice sheet.

During this stage the topography was modified by wave action which eroded the upland slopes and deposited sediments at the toes of the slopes. Figure 3 illustrates in more detail this erosion and deposition during the slope-wash stage.

Conclusion

The origin and environment of fossiliferous sediments similar to "stony clays" have for many years been subjects of much discussion and controversy. Normal sedimentation processes do not satisfactorily explain the concomitant deposition of extremely coarse and very fine sediments in the same environment. Many writers have referred to these fossiliferous "stony clays" in glaciated areas as fossiliferous tills and suggested they were formed by glaciers scouring and incorporating fossiliferous sea-floor muds. A few geologists, particularly in Europe, have taken exception to this hypothesis, and as a result other theories have been advanced. The writers have revived, modified, and enlarged upon some of these other theories and have proposed a composite theory to explain fossiliferous "stony clays".

The abundance of well-preserved marine fossils distributed more or less uniformly throughout the till-like "stony clay" deposits of the Lower Fraser Valley area led the writers to question the theory that the sediments were fossiliferous tills. As field data accumulated a changing environment of deposition became necessary to explain all the facies of "stony clays" with their distinct internal and external structural relations. As no one simple theory could explain the origin of the "stony clays" the following composite theory was arrived at to explain the field data.

Many of the unsorted, fossiliferous stony clay deposits are marine drift and were formed on the sea floor beneath a shelf-ice sheet. This shelf ice was one stage in the retreat of the Cordilleran ice sheet (5) which deposited the true till that underlies the "stony clay". During later stages of the ice sheet retreat the shelf ice gave way to berg ice and sea ice, and more marine drift was deposited. The remainder of the unsorted "stony clays" and their associated sorted sediments were formed as the land rose to its present position. During this phase the exposed till and marine drift were eroded by waves and in the low areas by current and oscillatory wave motions. This combination produced sediment which was transported and redeposited by turbidity or density currents, submarine landslides, and submarine currents. These deposits show an areal relation to the upland topography and the terraces cut into them.

References Cited

Archangelsky, A. D., 1935, Geologic structure of U. S. S. R.: United Scientific Tech. Publ., p. 195, 216.

Armstrong, J. E., and Tipper, H. W., 1948, Glaciation in north-central British Columbia: Am. Jour. Sci., v. 246, p. 283–310.

Bostock, H. S., 1948, Physiography of the Canadian Cordillera, with special reference to the area north of the fifty-fifty parallel: Geol. Survey Canada Mem. 247, p. 78–89.

Geikie, A., 1863, On the phenomena of the glacial drift of Scotland: Geol. Soc. Glasgow, Trans., v. 1, pt. 2, p. 129–148.

Johnston, W. A., 1923, Geology of Fraser River delta map-area, Geol. Survey Canada Mem. 135, p. 39–54.

Miller, D. J., 1953, Late Cenozoic marine glacial sediments and marine terraces of Middleton Island, Alaska: Jour. Geology, v. 61, p. 17–40.

Roots, E. F., 1952, The Norwegian-British-Swedish Antarctica Expedition 1949–52: Science News 26, Penguin Books, p. 9–32.

Geological Survey of Canada, 300 Pender St., W., Vancouver, B. C.

Manuscript Received by the Secretary of the Society, March 2, 1953

Published by Permission of the Director General of Scientific Services, Dept. of Mines and Technical Surveys, Ottawa, Ontario, Canada

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 65, 1 FIG., 365-368 APRIL 1954

Short Notes

LEMHI ARCH, A MID-PALEOZOIC POSITIVE ELEMENT IN SOUTH-CENTRAL IDAHO

By L. L. Sloss

Middle Paleozoic stratigraphy of the central Idaho area lying north of the Snake River plain and east of the Idaho batholith has been abundantly documented in the literature, chiefly through the efforts of C. P. Ross (1934; 1937; 1947). The general section, as shown on the accompanying columnar diagram (Fig. 1) with slight modifications in nomenclature by the writer, is as follows:

	Feet
Mississippian	
Milligen formation. Dark-gray to black shale and argillite with minor beds and lenses of conglomeratic subgraywacke.	700–7000
Upper Devonian	
Three Forks shale. Light-gray and tan to dark-gray shaly limestone and dolomite.	50
Middle and Upper Devonian	
Jefferson dolomite. Predominantly dark-gray to black massive dolomite with lighter-gray zones, and minor dolomitc sandstones near the top. [*Note:* Ross (1934) recognizes the upper light-colored beds as a separate formation, the Grand View dolomite. Further work may show that the three subdivisions described in the Gold Hill area (Nolan 1930; 1935) may be applicable to the south-central Idaho Devonian.]	2200
DISCONFORMITY	
Middle (?) Silurian	
Laketown dolomite. Light- to medium-gray dolomite with pink-stained zones.	1000
DISCONFORMITY	
Upper Ordovician	
Fish Haven dolomite. Medium- to dark-gray dolomite, sandy at the base. [*Note:* Ross (1934) named a more westerly argillitic equivalent the Saturday Mountain formation and applied that term throughout the area. As indicated by Ross, the eastern phase concerned here is more closely related to the dominantly carbonate Fish Haven of southeastern Idaho.]	700
Middle and Upper (?) Ordovician	
Kinnikinic quartzite. Massive, silica-cemented, pure quartzose sandstone.	2500

The character and thickness of the Middle Paleozoic strata represented between the Ordovician quartzites and the Mississippian argillites in the south-central Idaho section are similar to those encountered in the western ranges of the Rocky Mountain trend and in the adjacent areas of western Utah, southeastern Idaho, and eastern Nevada. This huge province of thick Middle Paleozoic sedimentation has been recognized as part of the Cordilleran geosynclinal system (Schuchert, 1923; Nolan, 1943), with further identification as the Nevada-Idaho basin (Eardley, 1947; 1951) and as the Millard miogeosynclinal belt (Kay, 1947; 1951). In general, reasonably consistent Middle Paleozoic thicknesses have been recorded throughout the province, except where Late Paleozoic and younger erosional episodes have removed part of the section (Sloss, 1952).

With this pattern in mind it is interesting to note a radical departure from regional

thickness trends in south-central Idaho. The significant exposures are on the west flank of the Lemhi Range (the first Idaho uplift west of the Montana border) near its southern tip and approximately 6 miles north of the village of Howe. The outcrops are readily accessible near the mouth of a small canyon just north of what is locally termed "Middle Canyon". Here the most southerly exposure in the Lemhi Range of the massive Kinnikinic quartzite, which forms a prominent white band on the mountain flank, passes under the alluvial fan. A summary of the section above the quartzite follows:

Southern Lemhi section
Sec. 3, T. 6 N., R. 29 E.
Butte County, Idaho

	Feet
Mississippian	
Milligen formation (in thrust (?) contact with Belt. Top not exposed.)	
1. Argillite, siliceous, black, thin-bedded; weathers light gray and rusty. Few thin beds black chert; scattered gray limestone concretions	200+
Devonian	
Three Forks shale	
2. Dolomite, shaly, thin-bedded, dark gray and black; weathers brown, yellow, and orange. Shale content increases toward transitional contact with Milligen. *Cyrtospirifer, Camarotoechia*, etc.	33
Jefferson dolomite	
3. Dolomite, dark gray, saccharoidal; massive with few minor solution breccia zones; weathers medium gray and brown	97
4. Partial cover with dolomite, shaly, thin-bedded, chiefly dark gray, dense, some light gray and maroon; weathers to bright-yellow, orange, and rusty chips	33
5. Limestone, dark gray and black, black weathering, saccharoidal; stemlike mottles and segregations of coarser (dolomite?) crystals. Six-inch rubble zone of dolomite pebbles at base resting on channeled surface of unit below	15
6. Dolomite, medium gray, finely saccharoidal; weathers light gray and tan. Few zones dark gray; medium saccharoidal, black weathering. Finely laminated near base. Few recrystallized coral fragments	137
7. Dolomite, medium gray, dense to finely saccharoidal; weathers light gray. Few zones dark gray	79
8. Sandstone, conglomeratic, brown; rounded pebbles of white quartzite and gray dolomite to 10 mm	3
9. Dolomite, dark gray, finely crystalline, dark gray weathering	66
10. Sandstone, quartzitic, tan; grains from ¼ mm to 4 mm; with gray dolomite and sandy dolomite lenses; gradational contact with unit above. Basal 1–2 feet conglomeratic with pebbles of Fish Haven dolomite to 4 cm; rests on channeled surface of unit below	10
Total thickness Jefferson dolomite	440
Ordovician	
Fish Haven dolomite	
11. Dolomite, dark gray, dense to finely crystalline; weathers to smooth dark-gray surfaces; numerous silicified brachiopod fragments and minute crinoid columnals. Scattered floating sand grains near base	41
Kinnikinic quartzite	
12. Sandstone, quartzitic with a few friable zones, white, medium-grained and well-sorted, massive	1000+

John M. Andrichuk (Personal communication, 1953) believes that unit 4 of the section represents the Three Forks shale and is repeated in unit 2 by a minor fault at the base of unit 3. The writer is unable to confirm this hypothesis, but the possibility remains that the thickness indicated above for the Jefferson is too great by approximately 130 feet. However, in adjacent areas of Montana (Sloss and Moritz, 1951) there are evaporitic zones near the top of the Jefferson, and these zones, in poor exposure, closely resemble unit 4 of the section just described.

Other problems of the Southern Lemhi section concern the position of the base of the Devonian and the possible occurrence of Silurian strata. Three disconformities are present above the top of the Fish Haven dolomite, and none is significantly more prominent than the others, insofar as can be determined from the limited information available. In the absence of valid paleontologic data it is possible that Silurian beds may be represented by units 9 and 10, or even by unit 6 through 10.

Several factors weigh against assignment of the beds in question to the Silurian. In the first

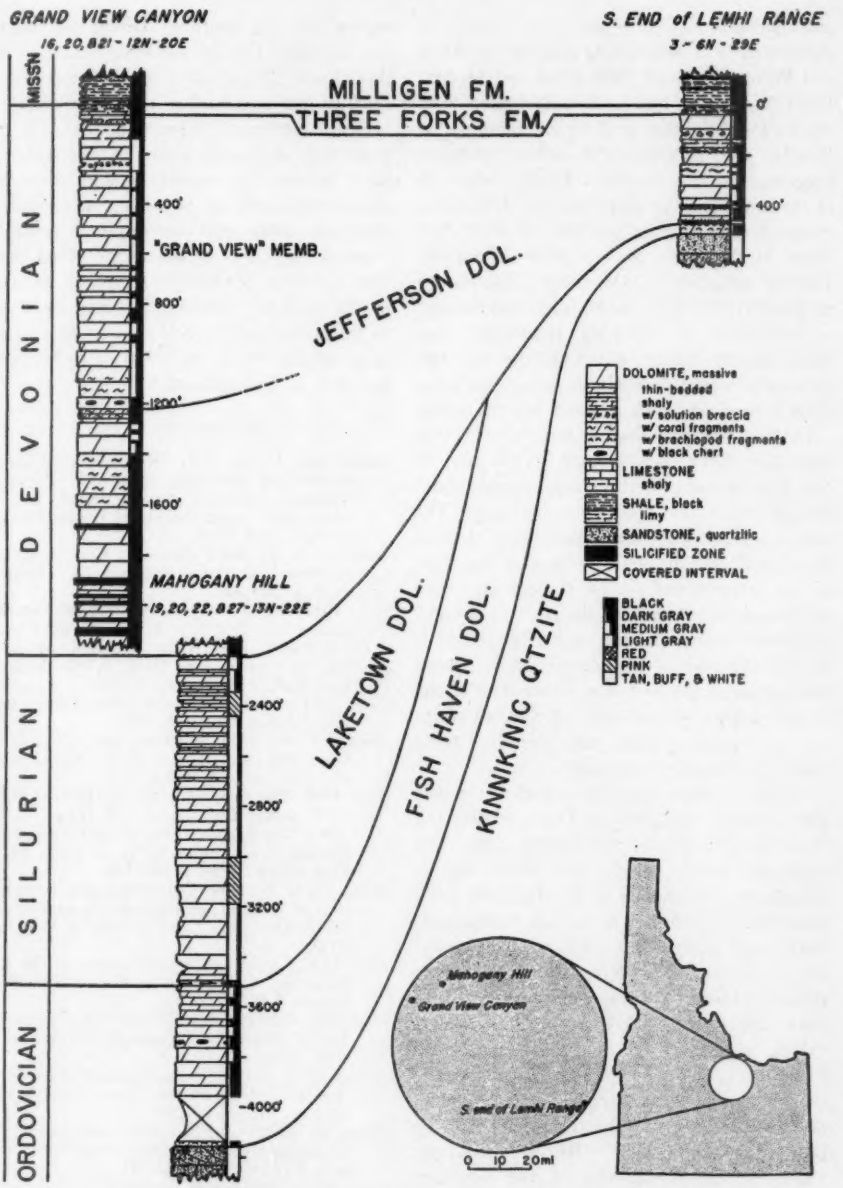

FIGURE 1.—STRATIGRAPHIC SECTIONS, SOUTH-CENTRAL IDAHO

place the dolomites involved are darker than those usually encountered in the Laketown in adjacent localities. Secondly, while disconformable relationships can be noted elsewhere at the base of the Laketown, the amount of pre-Middle Silurian erosion is not commonly of the magnitude suggested by the Southern Lemhi section Pre-Middle Devonian erosion

and unconformity, on the other hand, is characteristic of neighboring areas in Montana and Wyoming (Sloss, 1950; Sloss and Moritz, 1951; Andrichuk, 1951) where Devonian beds rest on Cambrian and even Precambrian rocks. Finally, the maximum Devonian thickness suggested for the Southern Lemhi section is of the same order of magnitude as thicknesses recorded on the more positive parts of shelf areas in Montana and western Wyoming. Further reduction of Devonian thickness by assignment of beds to the Silurian, and without a possibility of invoking significant pre-Mississippian erosion, would call for an even more pronounced anomaly in isopach patterns than is required by the present interpretation.

It thus appears that a positive element, here termed the Lemhi arch, was active in the western part of the south-central Idaho area in middle and upper Devonian time. The occurrence of sandstones seemingly derived from the Kinnikinic quartzite suggests exposure of the latter formation on the pre-Devonian surface on higher parts of the positive element and indicates that the section here presented is not on the crest of the feature. More precise delineation of the arch and unravelling of the relationships of Ordovician and Silurian strata to the pre-Devonian unconformity must await more detailed mapping.

Figure 1 illustrates the contrast between the "normal" south-central Idaho section and that encountered on the Lemhi arch. The composite section shown was chosen for its completeness, although it is about 60 miles from the Southern Lemhi section. Comparable thicknesses occur within 30 to 40 miles on the west flank of the Lost River Range and in the Donkey Hills at the head of the Little Lost River valley. Ross (1934, p. 953) has noted a "thick sequence" of dolomites, apparently Fish Haven, overlying the Kinnikinic quartzite in the Lemhi Range approximately 7 miles north of the section here concerned. At the base of the west flank of the Beaverhead Range, about 15 miles northeast of the Southern Lemhi section, there are a number of fault blocks involving Fish Haven, Laketown (?), and Jefferson dolomites. Accurate thicknesses are not obtainable, but the stratigraphic interval between the Kinnikinic and Milligen formations is obviously much thicker than that exposed at the Southern Lemhi section. On the Montana side of the Continental Divide the closest Devonian sections are twice as thick as that measured on the Lemhi arch.

Consideration of these data strongly suggests that the Lemhi arch is a relatively isolated feature not directly connected to the stable shelf area of Wyoming and southern Montana, unless such connection is concealed beneath the lavas of the Snake River plain. The apparent pre-Middle Devonian behavior of the element, however, is strikingly similar to that noted on the shelf area to the east and is at variance with the behavior to be anticipated in a "geosynclinal trend".

References Cited

Andrichuk, J. M., 1951, Regional stratigraphic analysis of Devonian System in Wyoming, Montana, southern Saskatchewan, and Alberta: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 2368–2408.

Eardley, A. J., 1947, Paleozoic Cordilleran geosyncline and related orogeny: Jour. Geology, v. 55, p. 309–342.

—— 1951, Structural geology of North America: Harper and Brothers, New York, pl. 3.

Kay, Marshall, 1947, Geosynclinal nomenclature and the craton: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1289–1293.

—— 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

Nolan, T. B., 1930, Paleozoic formations in the Gold Hill quadrangle, Utah: Wash. Acad. Sci. Jour., v. 20, p. 421–432.

—— 1935, The Gold Hill Mining District: U. S. Geol. Survey Prof. Paper 177, 172 p.

—— 1943, The Basin and Range province in Utah, Nevada, and California: U. S. Geol. Survey Prof. Paper 197-D, p. 141–196.

Ross, Clyde P., 1934, Correlation and interpretation of Paleozoic stratigraphy in south-central Idaho: Geol. Soc. America Bull., v. 45, p. 937–1000.

—— 1937, Geology and ore deposits of the Bayhorse region, Custer Co., Idaho: U. S. Geol. Survey Bull. 877, 161 p.

—— 1947, Geology of the Boarah Peak quadrangle, Idaho: Geol. Soc. America Bull., v. 58, p. 1085–1160.

Schuchert, C., 1923, Sites and nature of the North American geosynclines: Geol. Soc. America Bull., v. 34, p. 151–230.

Sloss, L. L., 1950, Paleozoic sedimentation in Montana area: Am. Assoc. Petroleum Geologists Bull., v. 34, p. 423–451.

—— 1952, Interpretive stratigraphy of the Great Basin (Abstract): Am. Assoc. Petroleum Geologists Program 37th Ann. Meeting, p. 23–24.

Sloss, L. L., and Moritz, C. A., 1951, Paleozoic stratigraphy of southwestern Montana: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 2135–2169.

Northwestern University, Evanston, Ill.